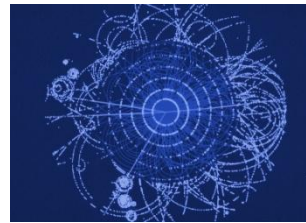
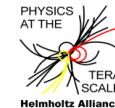


# Die Suche nach dem Ursprung der Masse mit dem Large Hadron Collider



Arno Straessner  
Institut für Kern- und Teilchenphysik

Physikalisches Colloquium  
TU Dresden  
Juni 2009



Deutsche  
Forschungsgemeinschaft  
DFG





- Einführung:
  - Das Standardmodell der Teilchenphysik
  - Das Konzept der Masse und des Higgs-Mechanismus
  - Aktuelles zum Higgs-Boson im Standardmodell
- Der Large Hadron Collider (LHC) und seine Experimente
- Suche nach Higgs-Bosonen mit ATLAS und CMS
- Die Zukunft: Super-LHC

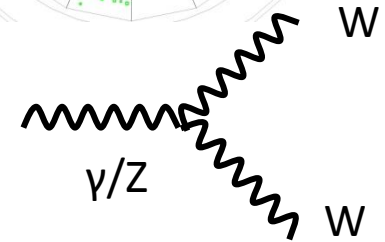
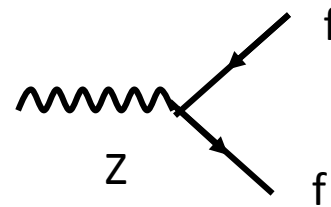
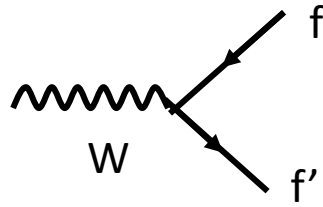
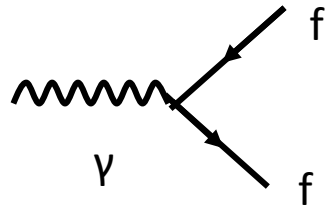
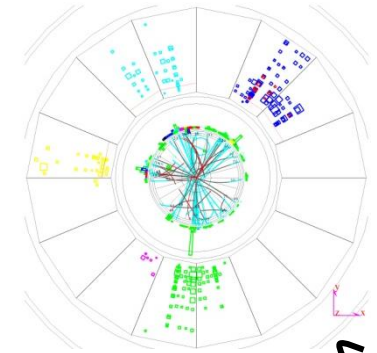
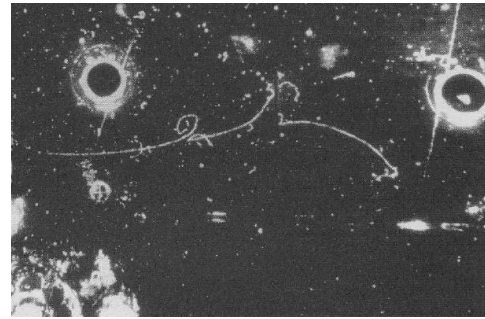
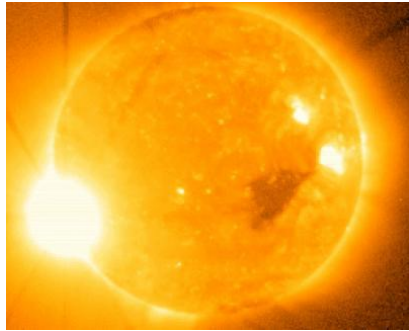
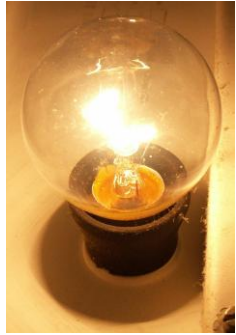


# Das Standardmodell

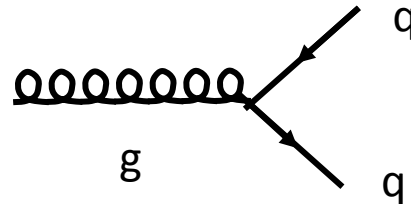
# Das Standardmodell



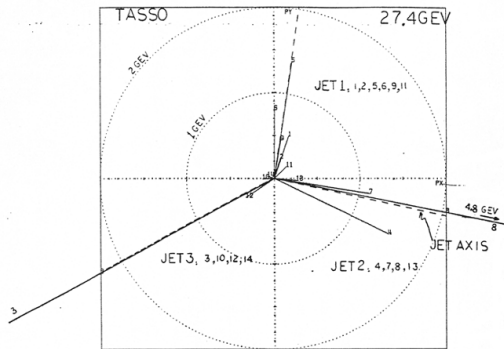
- Das Standardmodell beschreibt elektromagnetische, schwache und starke Wechselwirkungen → lokale Eichtheorie



elektroschwache Theorie  
mit Eich-Symmetrie  
→  $SU(2) \times U(1)$



Quantenchromodynamik  
→  $SU(3)$





# The PARTICLE ZOO

Handmade Subatomic Particle Plushies FROM THE STANDARD MODEL OF PHYSICS & beyond!  
 { ages 5 and up }

**LEPTONS**

**ELECTRON-NEUTRINO**  
This minuscule bandit is so light, he is practically massless.

**MUON-NEUTRINO**  
Like the other 2 neutrinos, he's got an identity crisis from oscillation.

**TAU-NEUTRINO**  
He's a tau now, but what type of neutrino will he be next?

**NEW EDITION! ELECTRON**  
A familiar friend, this negatively charged, busy li'l guy likes to bond.

**MUON**  
A "heavy electron" who lives fast and dies young.

**TAU**  
A "heavy muon" who could stand to lose a little weight.

**QUARKS**

**UP QUARK**  
A teeny little point inside the proton and neutron, it is friends forever with the down quark.

**DOWN QUARK**  
A tiny little point inside the proton and neutron, it is friends forever with the up quark.

**CHARM QUARK**  
A second generation quark, he is charmed, indeed.

**STRANGE QUARK**  
What's so strange about this second generation quark?

**TOP QUARK**  
This heavyweight champion doesn't live long enough to make friends with anyone.

**BOTTOM QUARK**  
This third generation quark is puttin' on the pounds.

**PHOTON**

His eyes red from traveling so fast, the **PHOTON** is a quanta of visible light, a wave particle that communicates the electromagnetic force, traveling at the speed of light (ahh). With a mass and electric charge of zero, it also carries microwaves, radio waves and X-rays.

*Acrylic felt with poly fill for maximum mass.*

**\$9.75** PLUS SHIPPING

●○○○○○○○○○○○●  
LIGHT HEAVY

**W BOSON** *W<sup>-</sup>, W<sup>+</sup>*

The **W BOSON** is a messenger particle which communicates the weak force. Unlike the photon and gluon bosons, it has a mass. Like the Z boson, it is one of the most short-lived particles known, with a mere 10<sup>-25</sup> second lifetime. It can be negatively charged (W<sup>-</sup>) or positively charged (W<sup>+</sup>). Luckily you can have both, as the toy is double-sided.

*Wool felt with gravel fill for maximum mass.*

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**Z BOSON** *Z*

The **Z BOSON** is a very massive carrier particle for the weak force. Unlike its siblings the W<sup>+</sup> and W<sup>-</sup> particles, the Z is neutrally charged. Living only 10<sup>-25</sup> seconds, the Z quickly decays into other particles.

Discovered in 1983, the Z boson has allowed physicists to further study electroweak theory.

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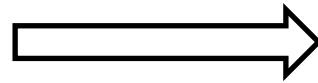
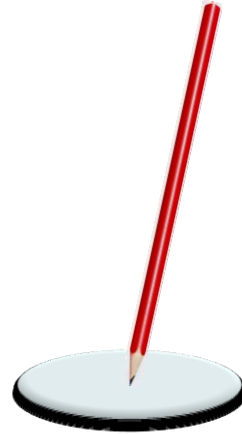
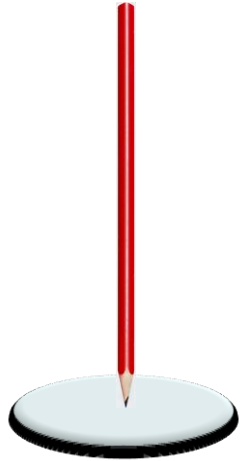
Das Standardmodell in der einfachsten Form hat ein Problem:

- einfachste Formulierung mit massiven Teilchen bricht explizit die SU(2) x U(1) Eich-Symmetrie

- Teilchen sind ursprünglich masselos

→ widerspricht dem Experiment

# Spontane Symmetriebrechung



Das physikalische System besitzt Symmetrie  
hier: Rotationssymmetrie

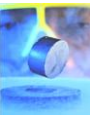
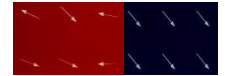
Der Grundzustand ist nicht symmetrisch

- Heisenberg 1928:
- Bardeen, Cooper, Schrieffer 1957:
- Nambu, Jona-Lasigno 1960, Goldstone 1961:

Ferromagnetismus

Supraleitung

Massen von Nukleonen



- Higgs, Englert & Brout, Guralnik & Hagen & Kibble 1964:

Anwendung auf das Standardmodell

→ Massen der W- und Z-Bosonen

# Das Higgs-Boson

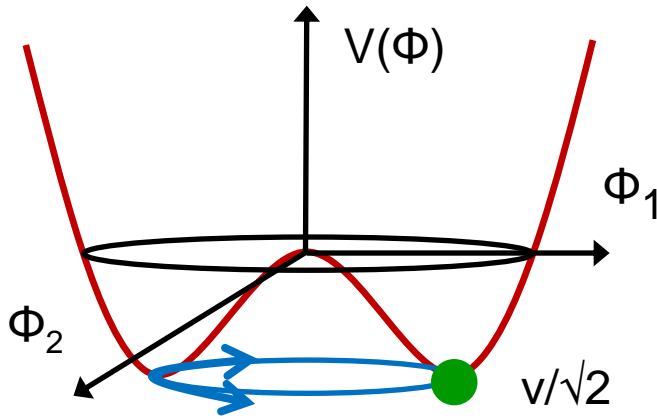
## BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

- Feld  $\Phi$  in Potential mit  $SU(2) \times U(1)$  Symmetrie:  $\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}$  Higgs-Duplett



- Grundzustand: Symmetriebrechung

$$\rightarrow \langle 0 | \Phi | 0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

- Massen für W- und Z-Bosonen festgelegt
- Massen für Fermionen frei

$$m_{W,Z} \sim v$$

$$m_f \sim y_f v$$



# Das Higgs-Boson

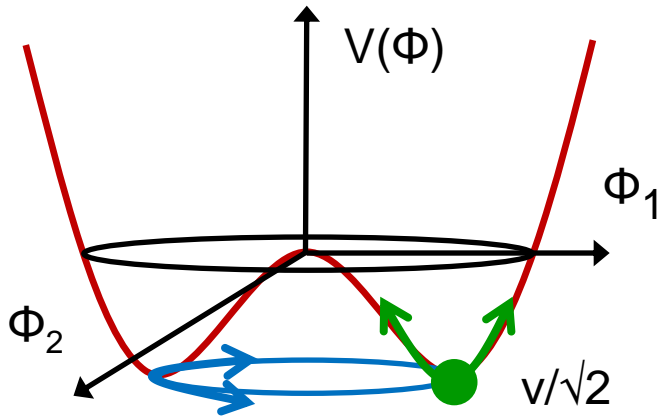
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- Massen für W- und Z-Bosonen festgelegt
- Massen für Fermionen frei

$$m_{W,Z} \sim v$$

$$m_f \sim y_f v$$

- Anregungen: **das Higgs-Boson**



$$\rightarrow \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

- Masse des Higgs-Bosons  $m_H \sim \lambda v$

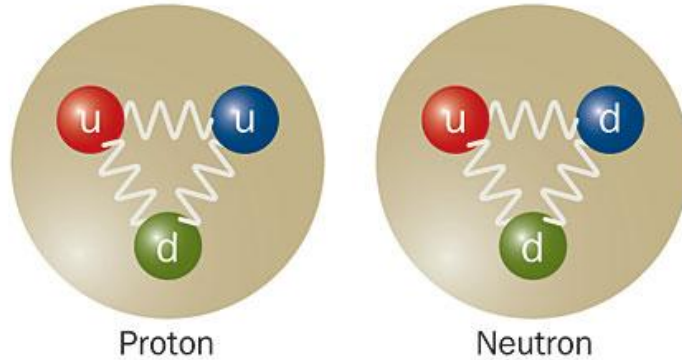
- Vakuumerwartungswert  $v = 246 \text{ GeV}$

# Sichtbare Masse im Alltag

## → Starke Wechselwirkung (QCD)

- Massenskala:

$$m_{\text{Atom}} \sim A \cdot m_{\text{Nukleon}}$$

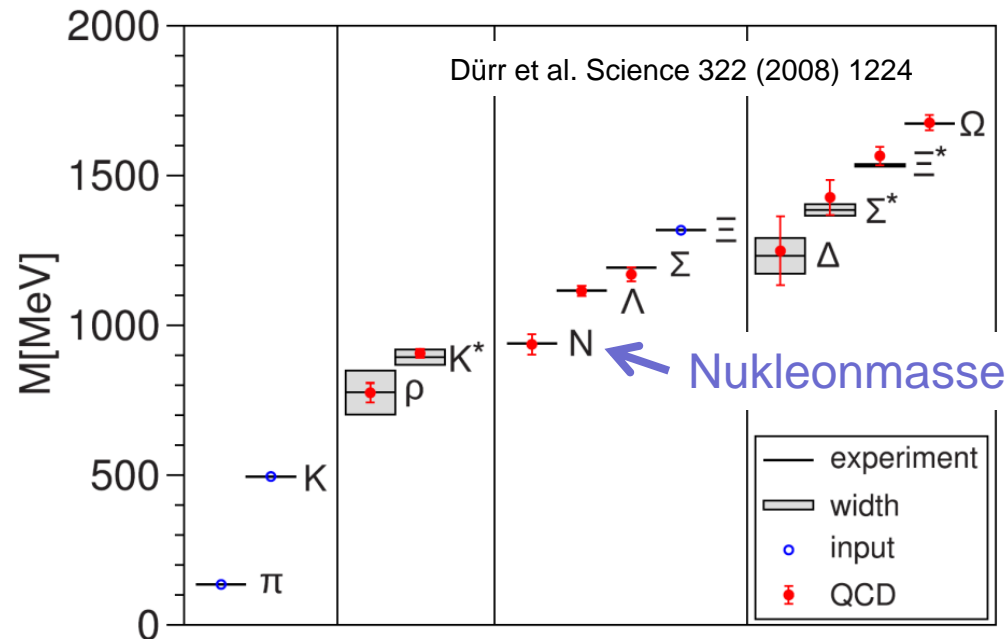


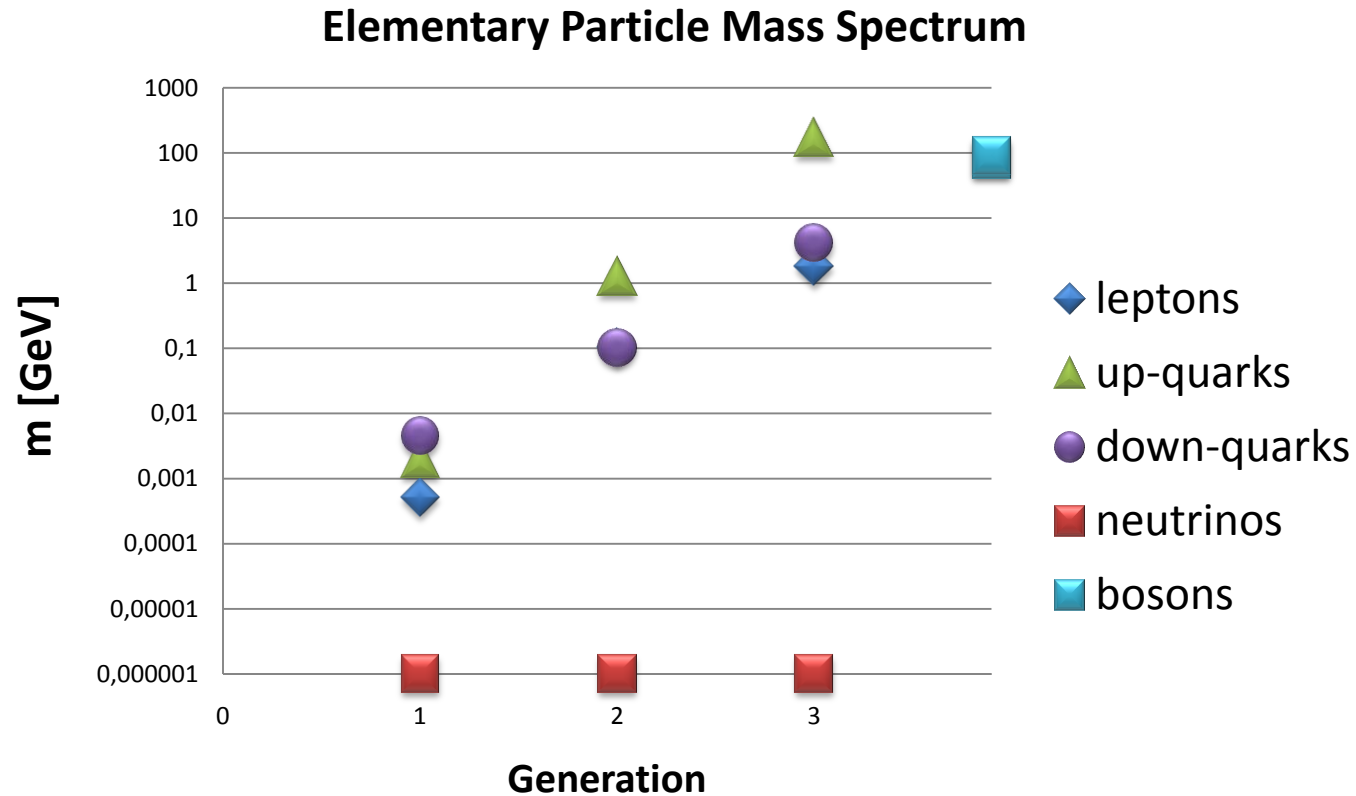
$$m_{\text{Nukleon}} \sim 200 m_{\text{Quark}} \sim 2000 m_{\text{Elektron}}$$



- Nukleonen und Hadronen

- Bindungszustände von Quarks und Gluonen
- Masse durch Bindungsenergie

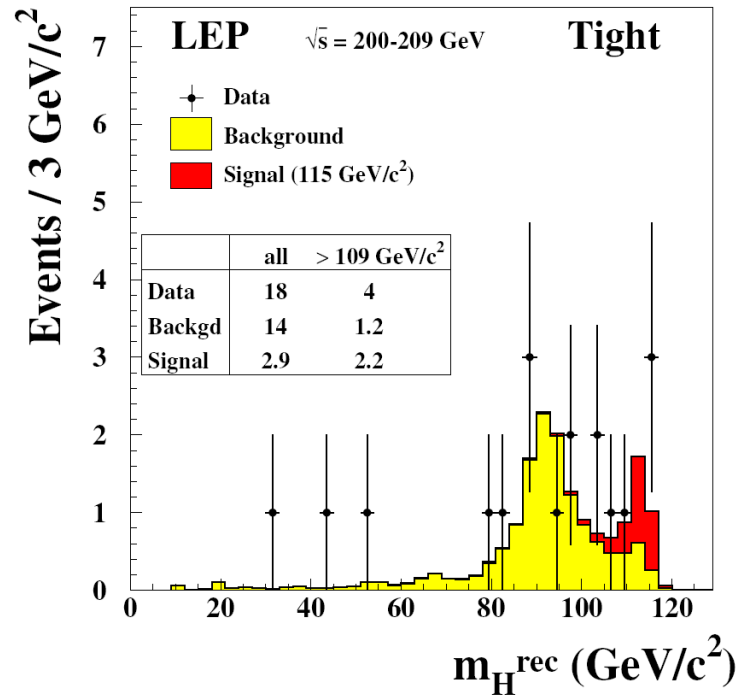
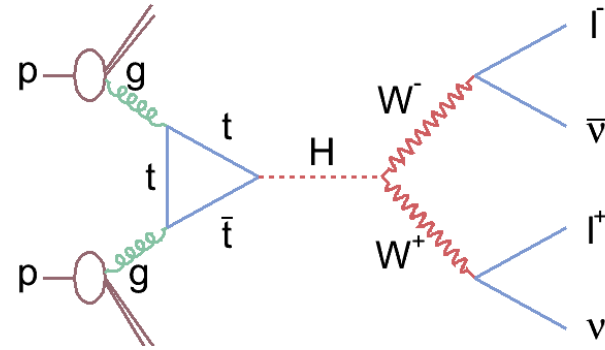
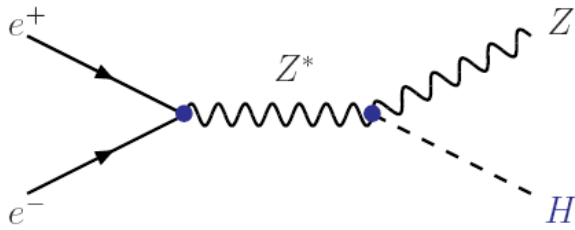




- Higgs-Feld → Massive Eichbosonen  
→ Dirac-Masse der Fermionen
- Neutrinos: Dirac-Masse → “normale” Fermionen  
Majorana-Masse → Neutrino = Antineutrino →  $0\nu\beta\beta$  – Zerfall  
→ Modelle mit Higgs-Tripletts (jenseits des SM)

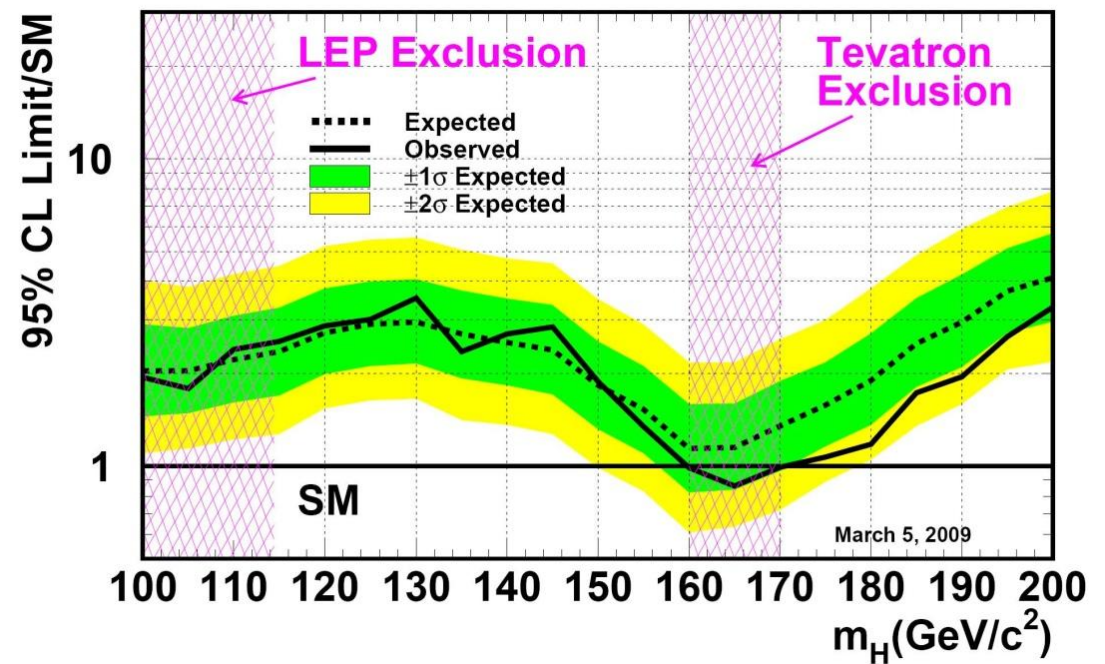
# Aktuelles zum Higgs im Standardmodell

# Direkte Suche bei LEP und Tevatron



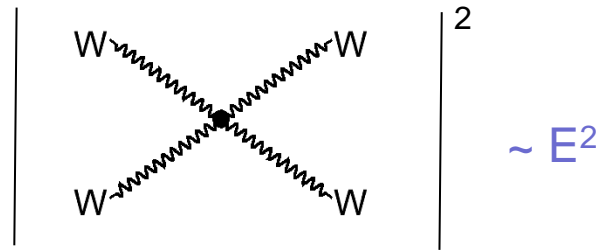
LEP:  $m_H > 114.4 \text{ GeV}$   
@ 95% CL

Tevatron Run II Preliminary,  $L=0.9-4.2 \text{ fb}^{-1}$

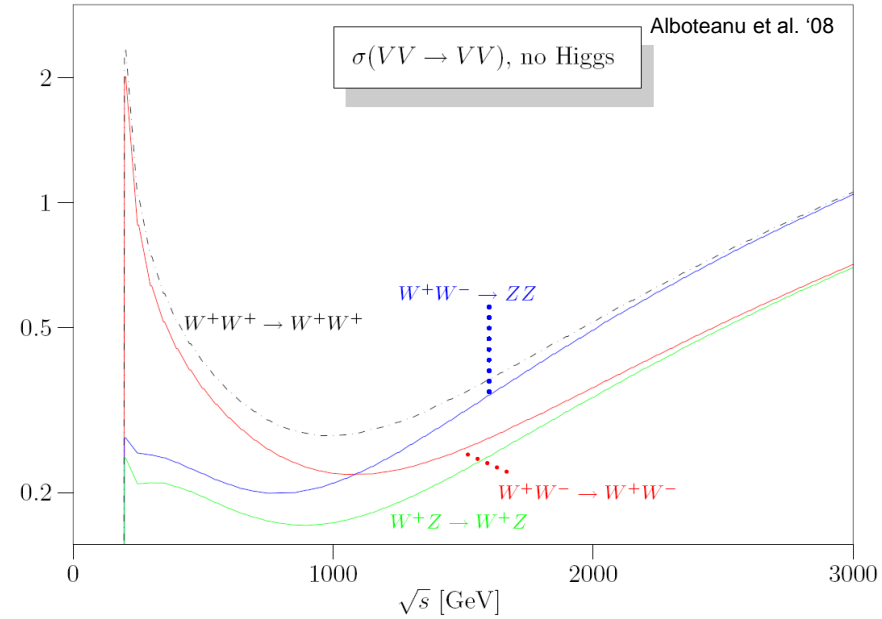
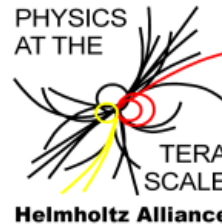


Tevatron:  $160 \text{ GeV} < m_H < 170 \text{ GeV}$  ausgeschlossen  
@ 95% CL

- sehr allgemeine Grenze:
- Vektor-Boson-Streuung z.B.  $WW \rightarrow WW$  verletzt Unitarität bei  $\sim 1$  TeV



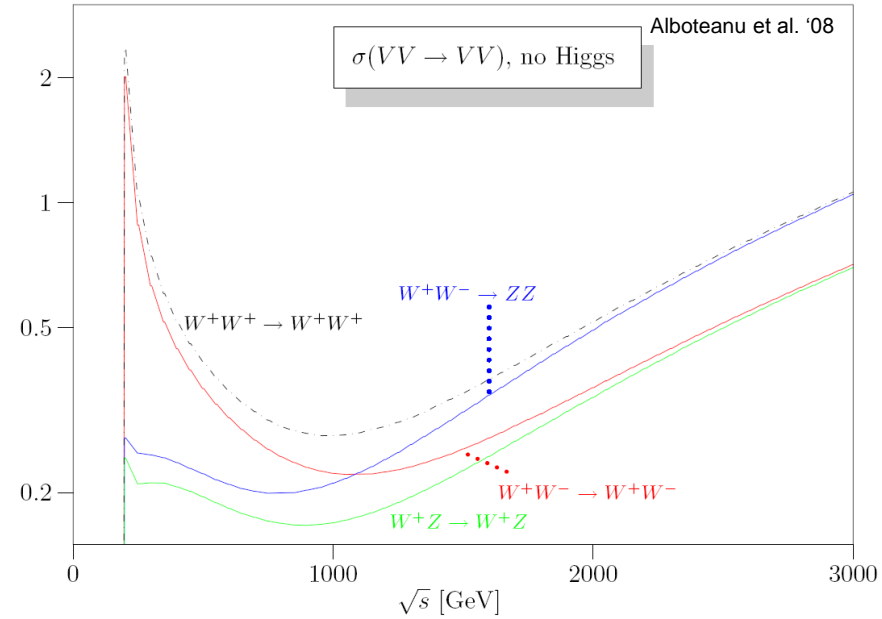
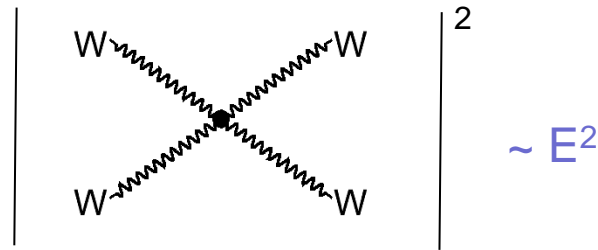
1 TeV  $\rightarrow$  Skala neuer Physik:  
Higgs, Supersymmetrie, ...



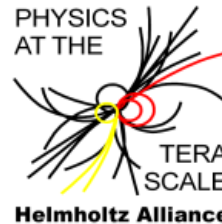


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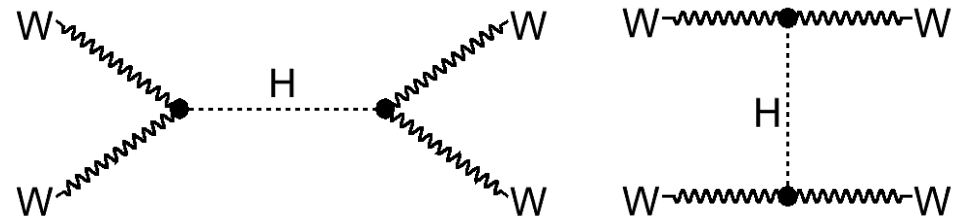
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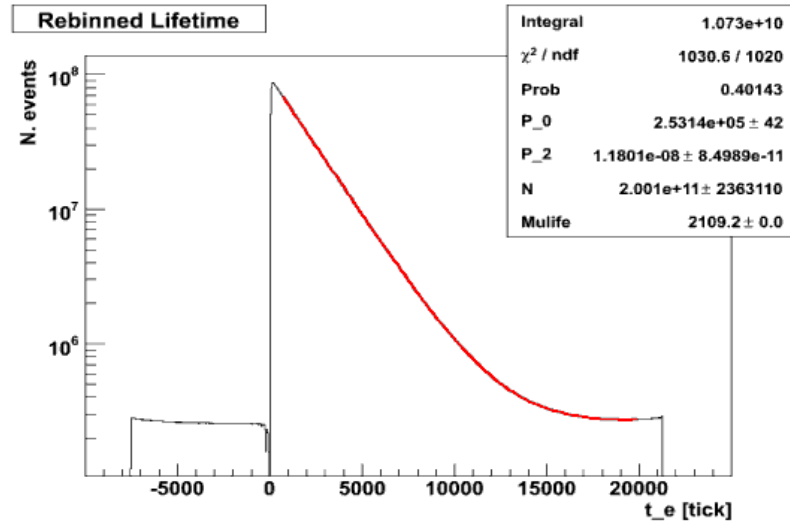
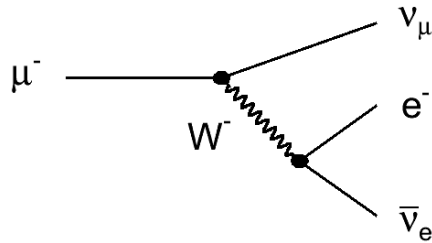
- Unitaritätsbedingung erfüllt, wenn Higgs-Boson existiert mit  $m_H < 710$  GeV



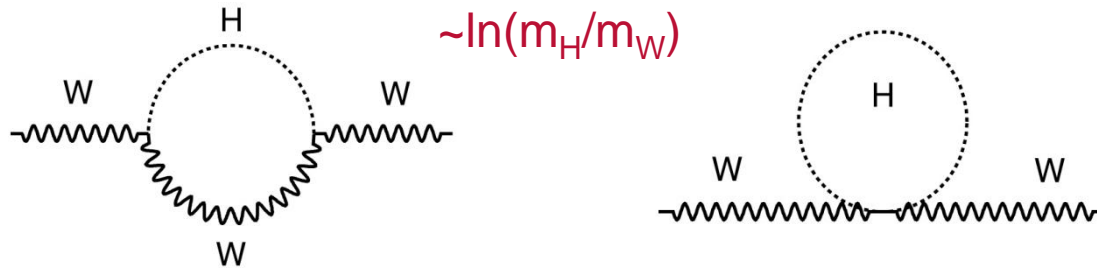
# Indirekte Einschränkungen der Higgs-Masse

- Strahlungskorrekturen zu elektro-schwachen Prozessen:

- z.B. Myon-Lebensdauer

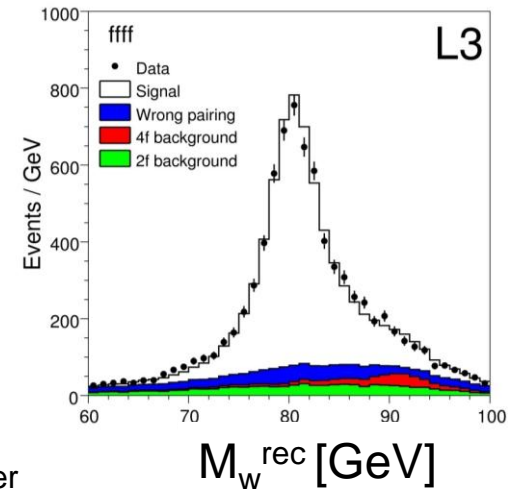


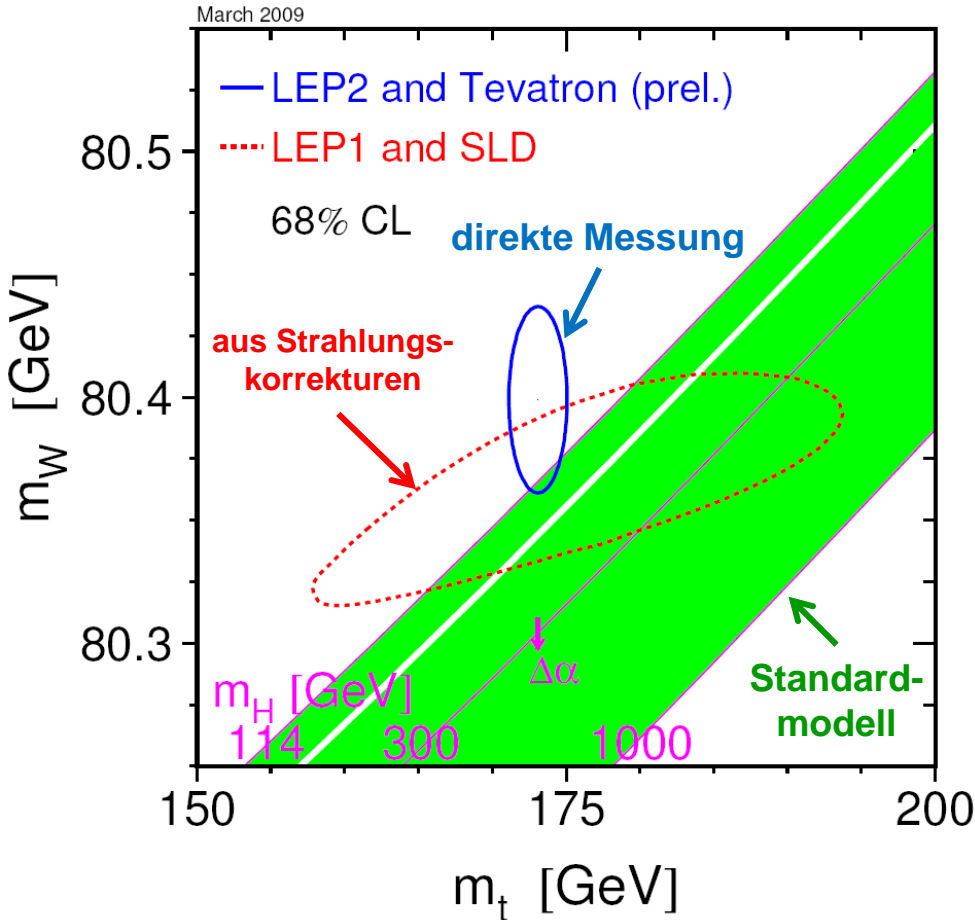
- Schleifenkorrekturen zum W-Propagator hängen von  $m_H$  ab:

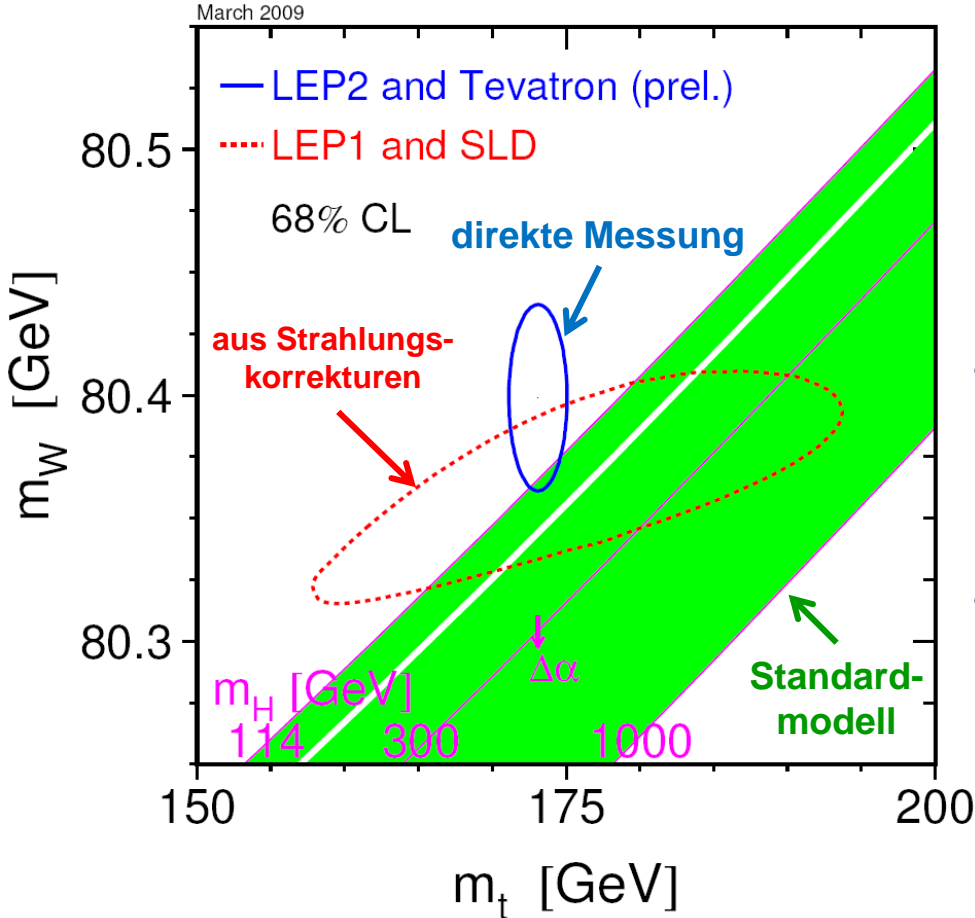


- sehr genaue Messungen der Standardmodell-Parameter nötig:

$$m_Z, m_W, m_{\text{top}}, \alpha_{\text{QED}}(Q^2), \alpha_s(Q^2)$$





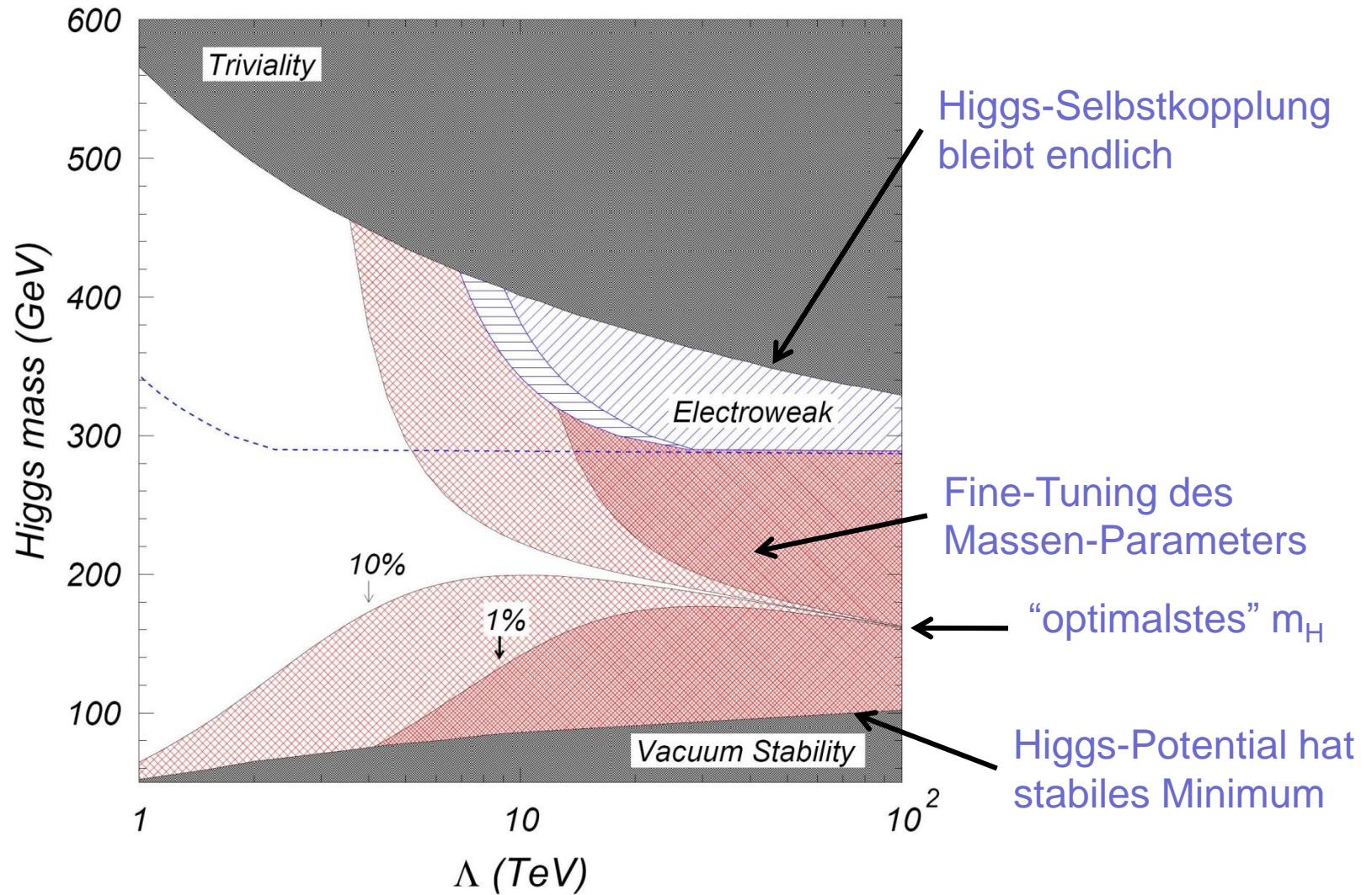


- größte Abweichung einer Einzelmessung:
  - anomales magnetisches Moment des Myons  $a_\mu = (g-2)/2$
  - Abweichung  $\sim 3.6 \sigma$  [Rafael arXiv:0809.3085v1]
  - insensitiv auf  $m_H$
- sehr sensitiv auf neue Physik:
  - Supersymmetrische Beiträge bringen gute Übereinstimmung
- Supersymmetrische Higgs-Bosonen:
  - 2 Higgs-Dupletts
  - 5 Higgs-Bosonen:
    - neutral:  $h, H, A$
    - geladen:  $H^\pm$

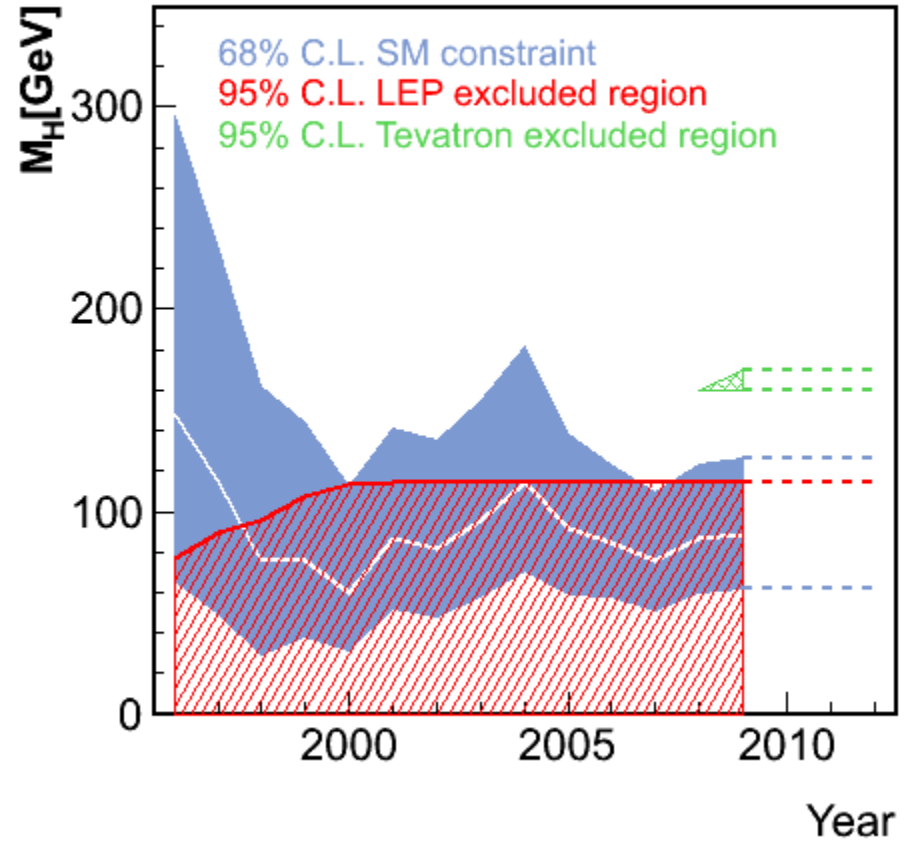
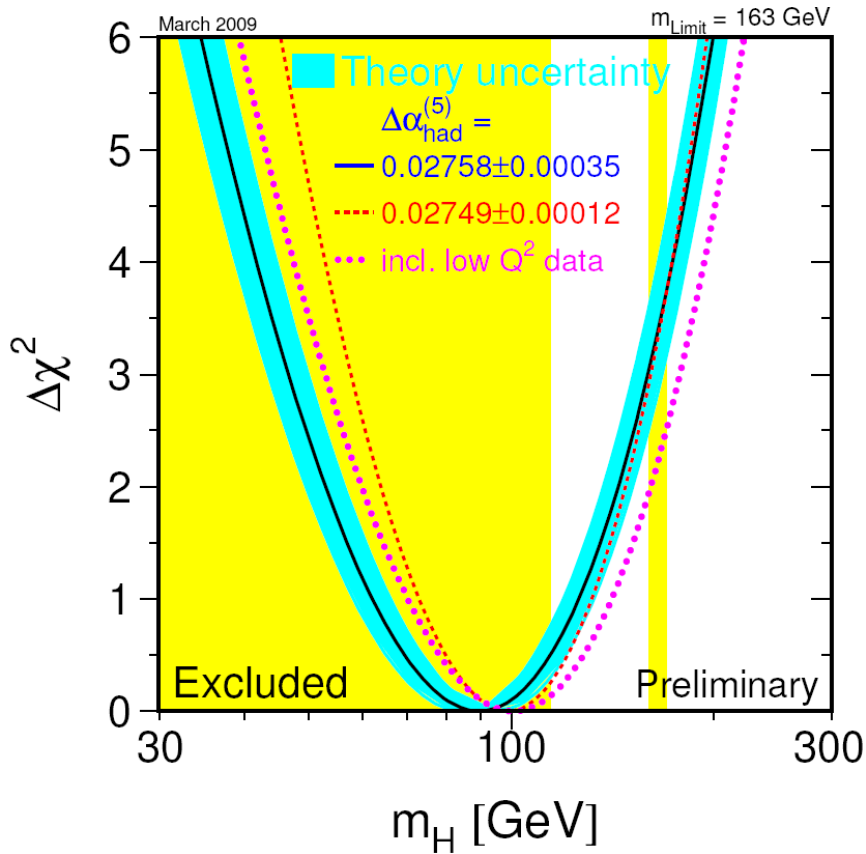
# Kann das SM bis zu hohen Energien gelten?



Kolda, Murayama '00



# Masse des Higgs-Bosons im SM

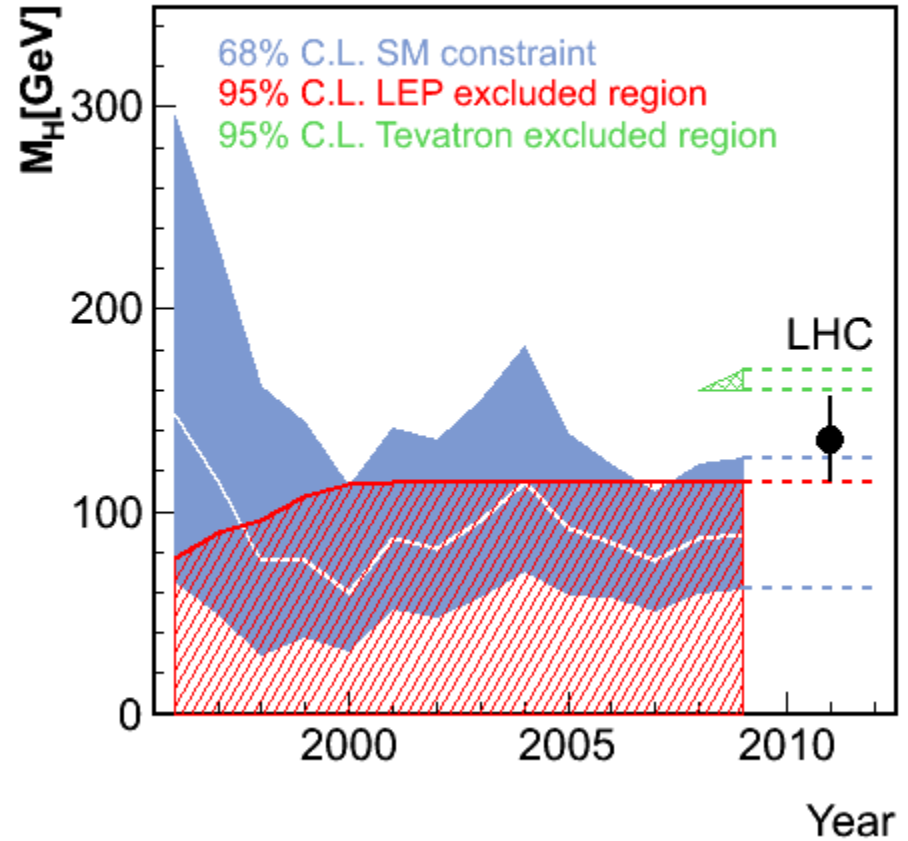
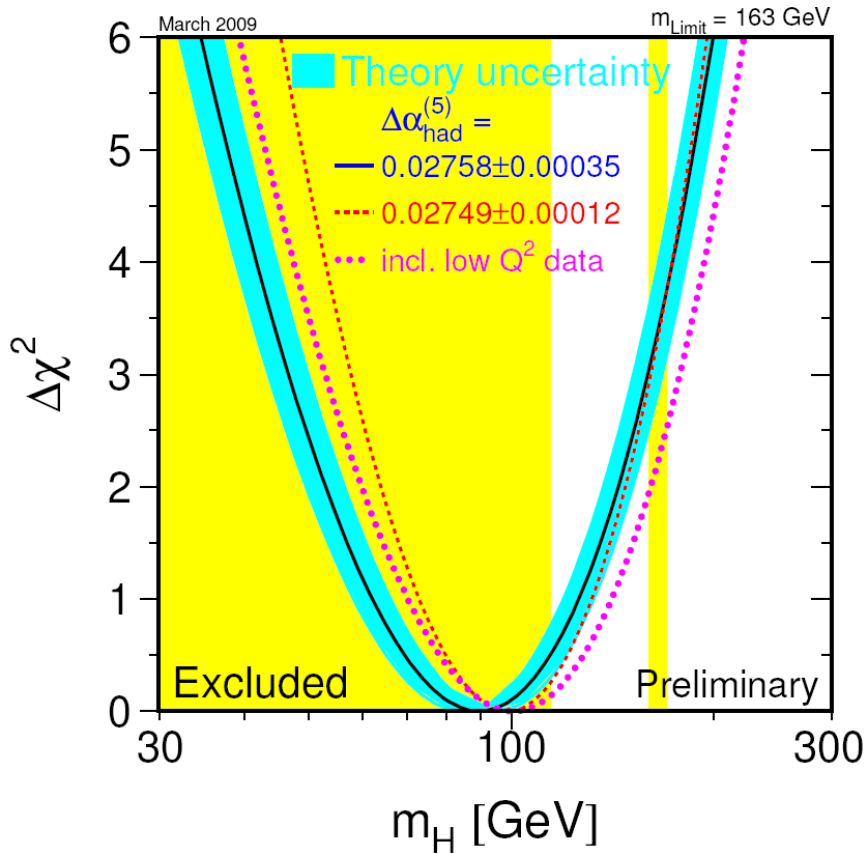


Fit an elektro-schwache Daten:  $m_H = 90^{+36}_{-27}$  GeV

oder  $m_H < 163$  GeV  
@ 95% CL



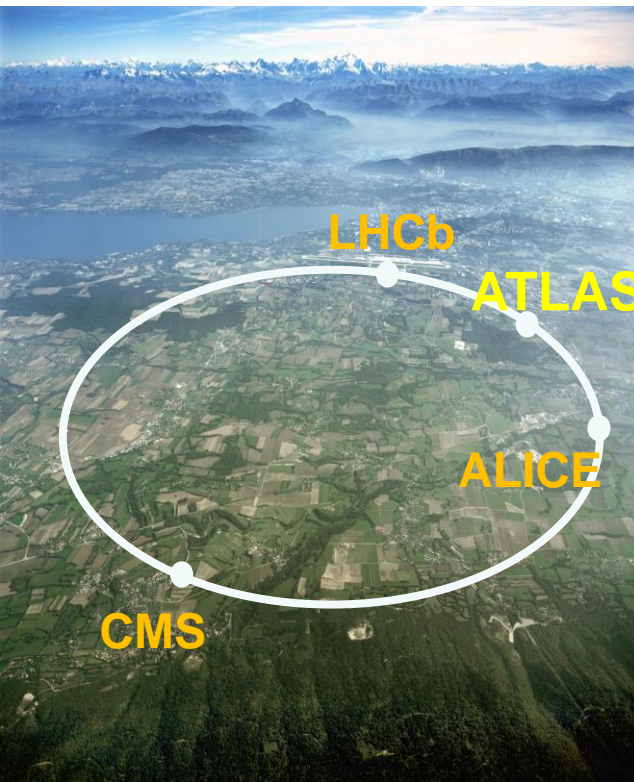
# Masse des Higgs-Bosons im SM



# Higgs-Physik am LHC



# Der Large Hadron Collider



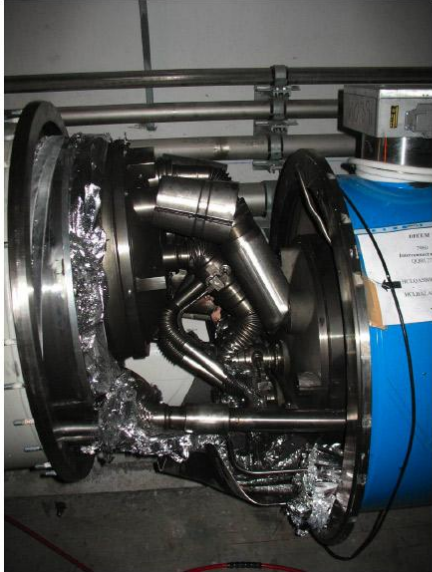
- 2808 Teilchen-Pakete mit je  $10^{11}$  Protonen pro Strahl
- alle 25 ns eine Strahl-Kreuzung
- Luminosität:  $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Energie pro Strahl: 362 MJ



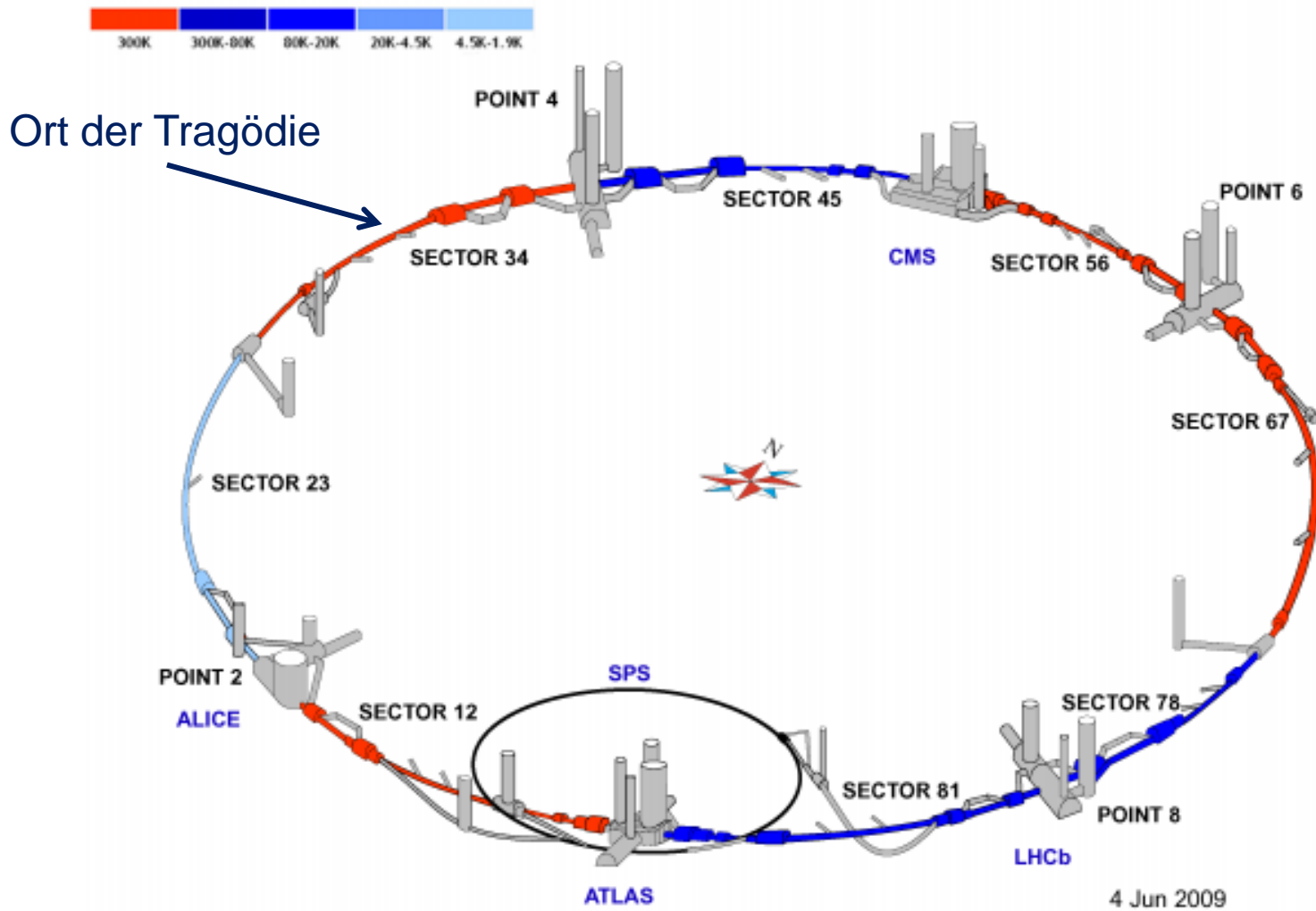
- 1232 supraleitende Dipolmagnete (15 m, 35 t):
  - gekühlt auf 1.9 Kelvin
  - max. Magnetfeldstärke: 8.35 T
- 120 t supra-fluides Helium
- gespeicherte Energie: 11 GJ



- Unfall während eines Strahltests bei 5 TeV:
  - Dipol-Quadrupol-Verbindung wurde normalleitend
  - Loch in die Vakuumisolation → unkontrolliertes Heliumleck
  - Resultat:



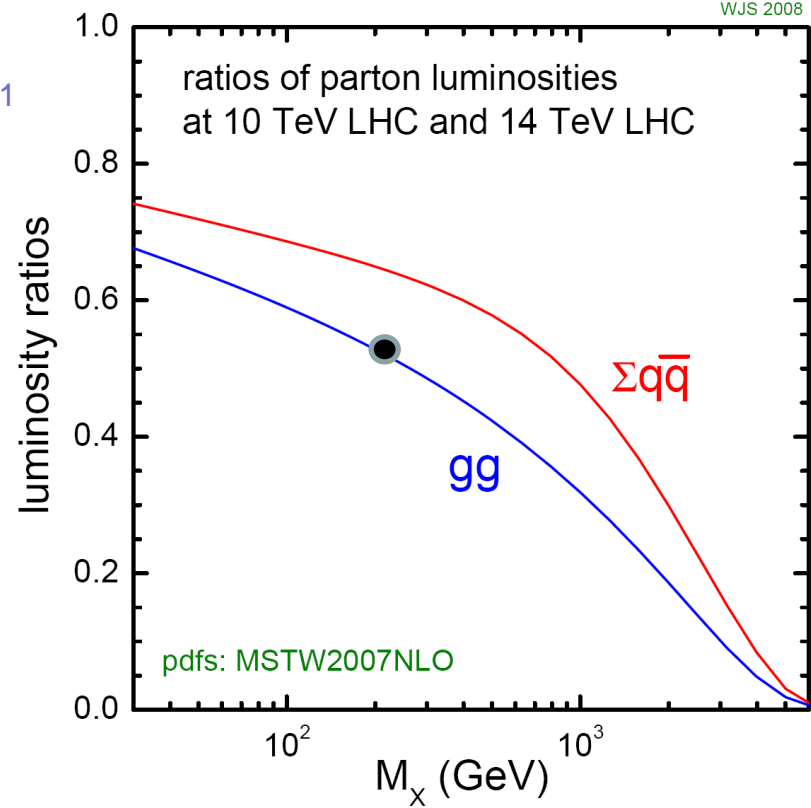
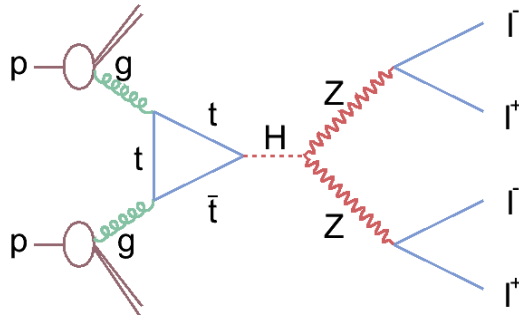
- 53 Magnete wurden an die Oberfläche gebracht, repariert und wieder installiert
- neue Druck-Ventile, neue Methoden zur präzisen Widerstandsmessung (kalt, warm)
- aktuell: elektrische und mechanische Magnet-Verbindungen werden wieder hergestellt  
→ Abkühlen kann bald wieder beginnen



- Neustart: August 2009 – Detektoren in “Commissioning Mode”  
September 2009 – LHC “second beam”

- Datennahme 2009/2010 ohne Winter-Pause
- Schwerpunktsenergie  $\sqrt{s}=10 \text{ TeV}$  ,  $\int L = 200 \text{ pb}^{-1}$

- aber nicht nur Proton-Proton-Luminosität zählt:  
→ Parton-Luminosität → Kollisionsenergie

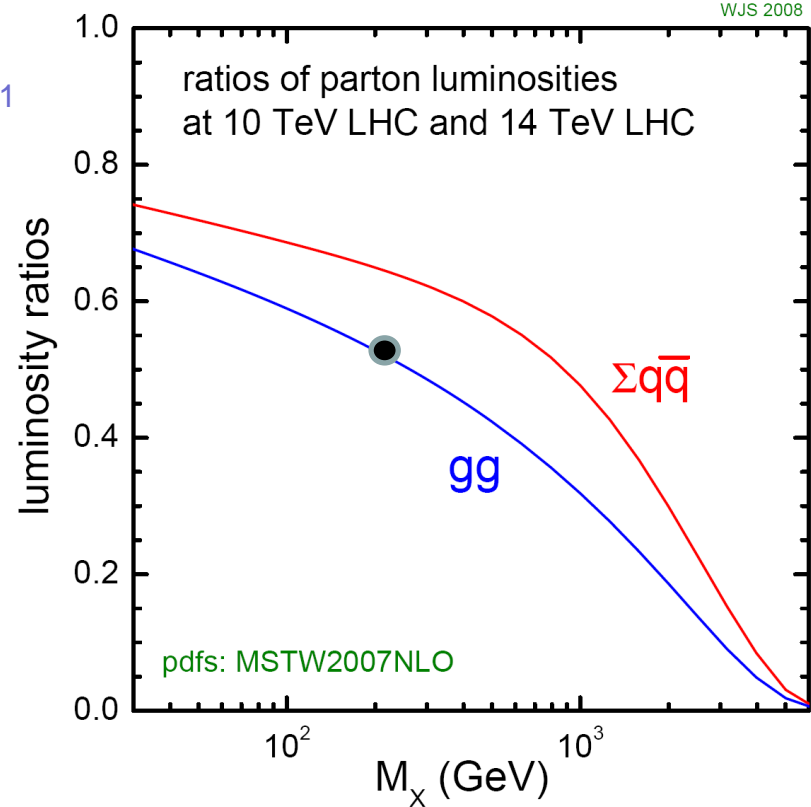
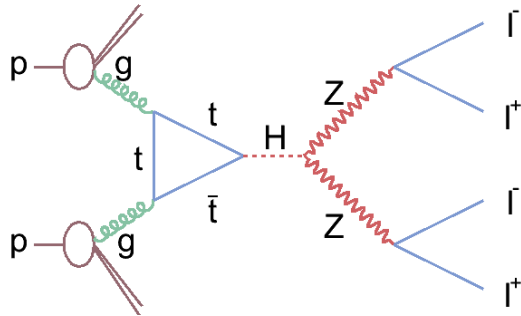




- Neustart: August 2009 – Detektoren in “Commissioning Mode”  
September 2009 – LHC “second beam”

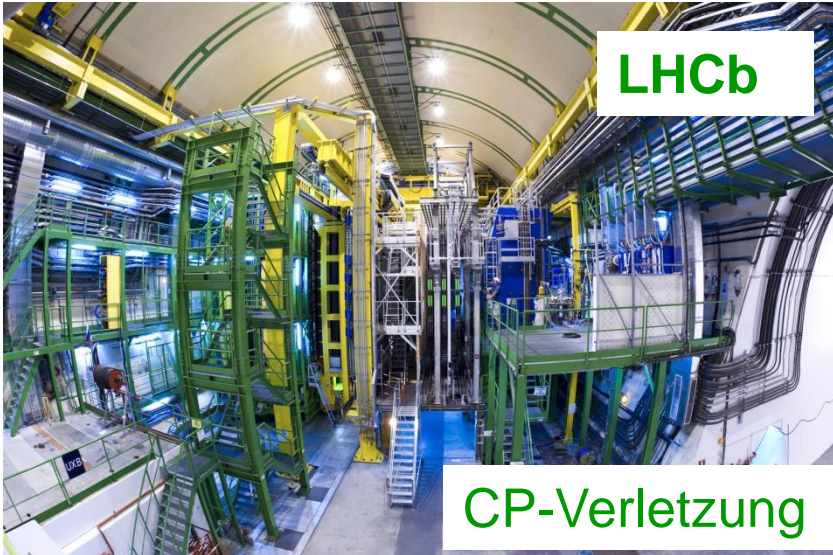
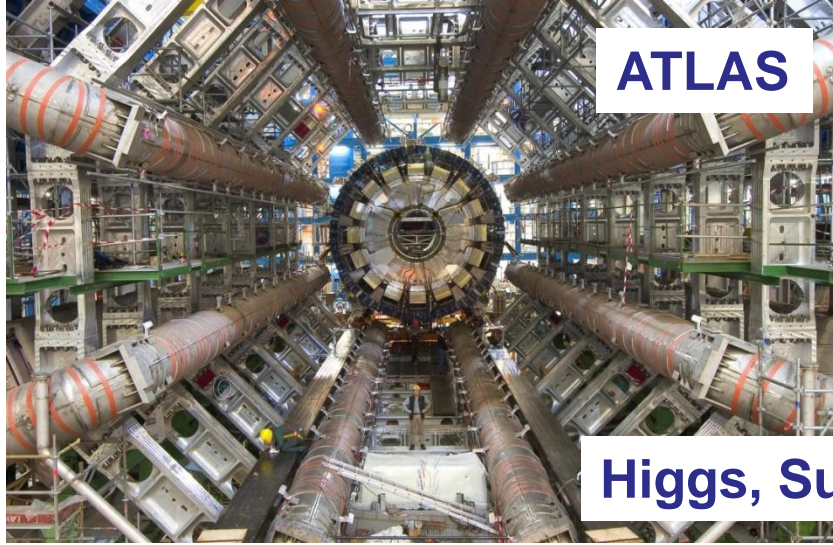
- Datennahme 2009/2010 ohne Winter-Pause
- Schwerpunktsenergie  $\sqrt{s}=10$  TeV ,  $\int L = 200$  pb<sup>-1</sup>

- aber nicht nur Proton-Proton-Luminosität zählt:  
→ Parton-Luminosität → Kollisionsenergie



- 2011/2012:  $\sqrt{s}=14$  TeV ,  $\int L = x \cdot 1$  fb<sup>-1</sup> pro Jahr
- 2012/2013-2016:  $\sqrt{s}=14$  TeV ,  $\int L = 80-100$  fb<sup>-1</sup> pro Jahr

# Die LHC-Experimente

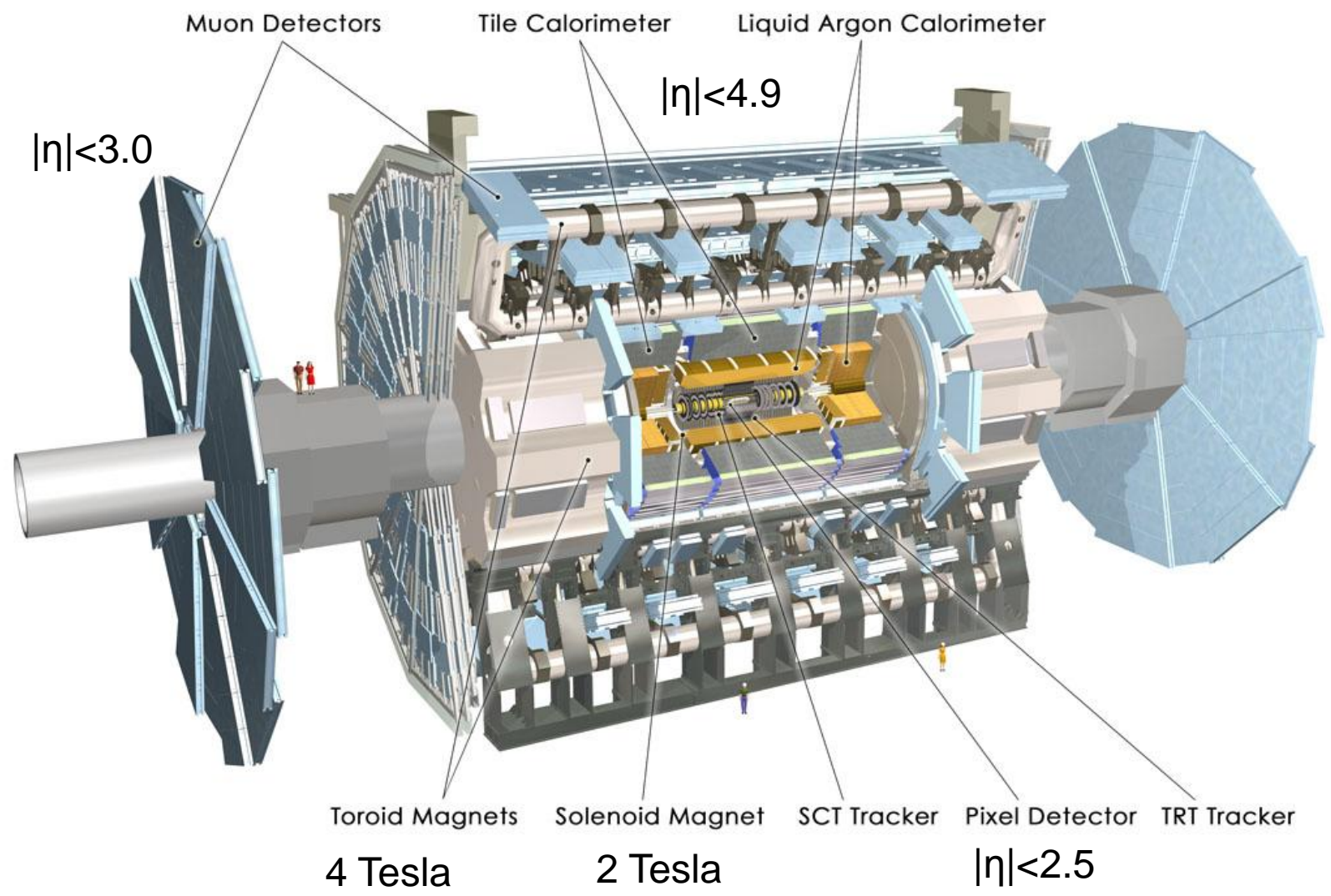




# Der ATLAS-Detektor

• Größe: 46m x 22m x 22m

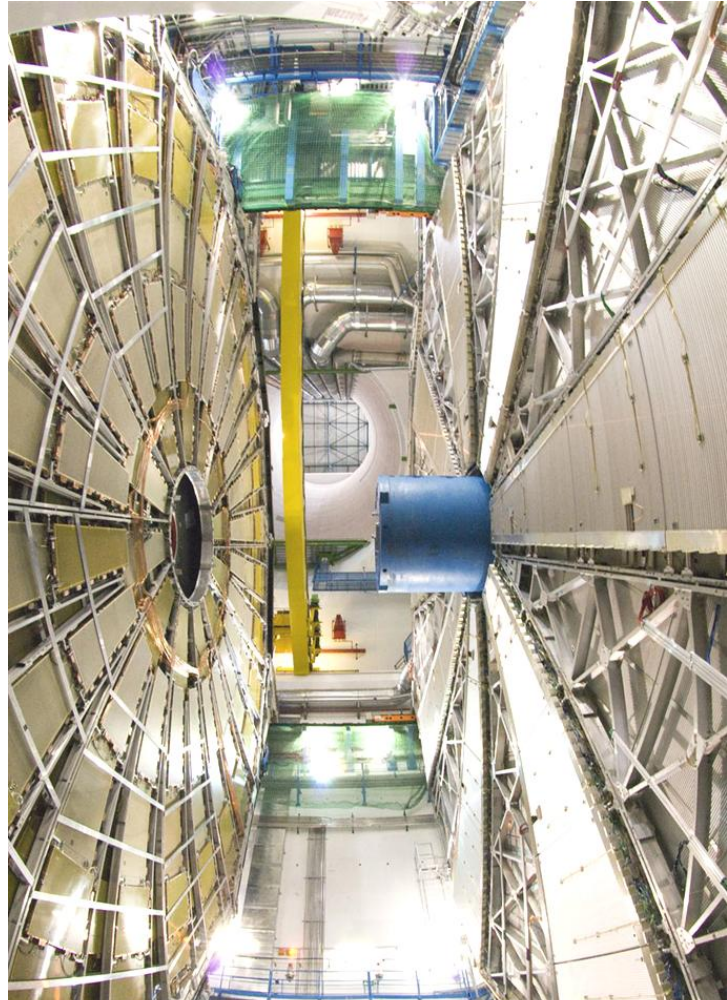
• Gewicht: 7000 t



$$\eta = -\ln(\tan(\theta/2))$$



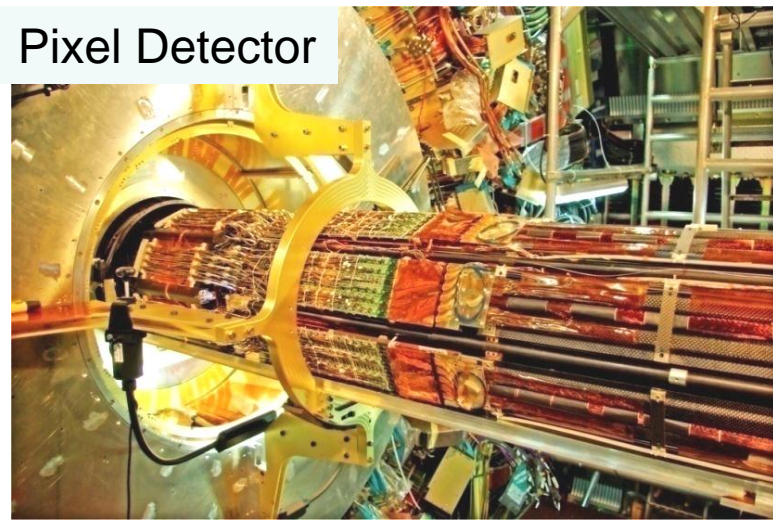
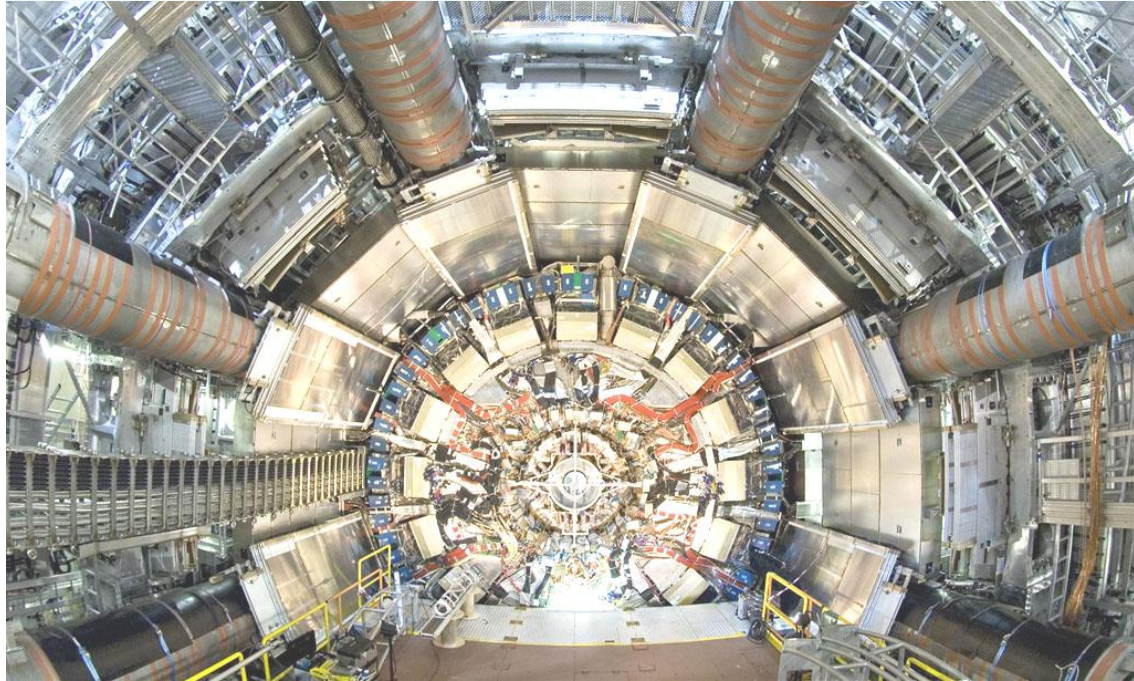
# Das ATLAS Experiment beim Aufbau



TGC und MDT Myon-Spektrometer

MDT=Monitored Drift Tubes  
TGC=Thin Gap Chambers  
SCT=Semiconductor Tracker

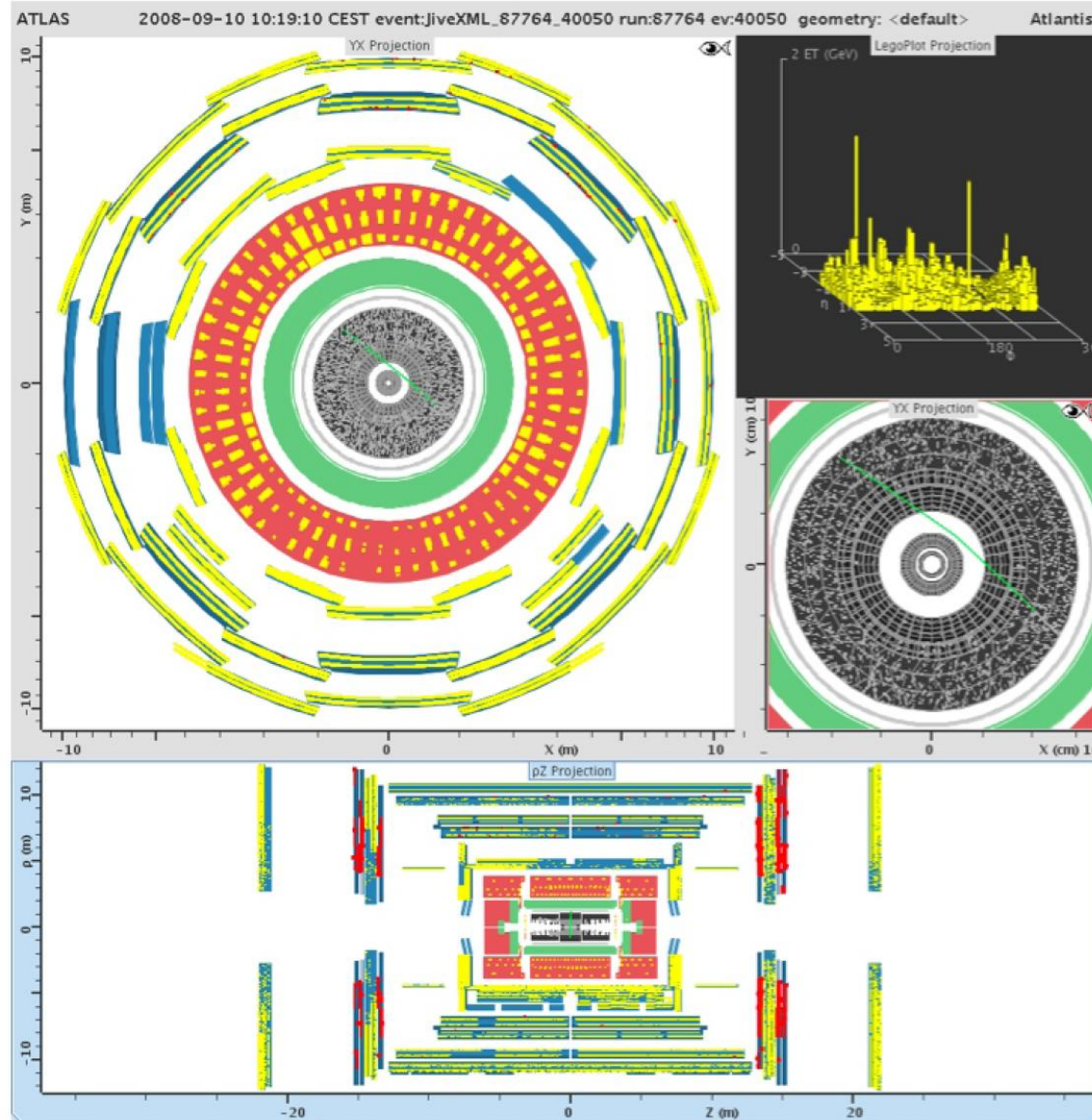
Toroid-Magnet - LAr-Kalorimeter - SCT Endkappe



Pixel Detector



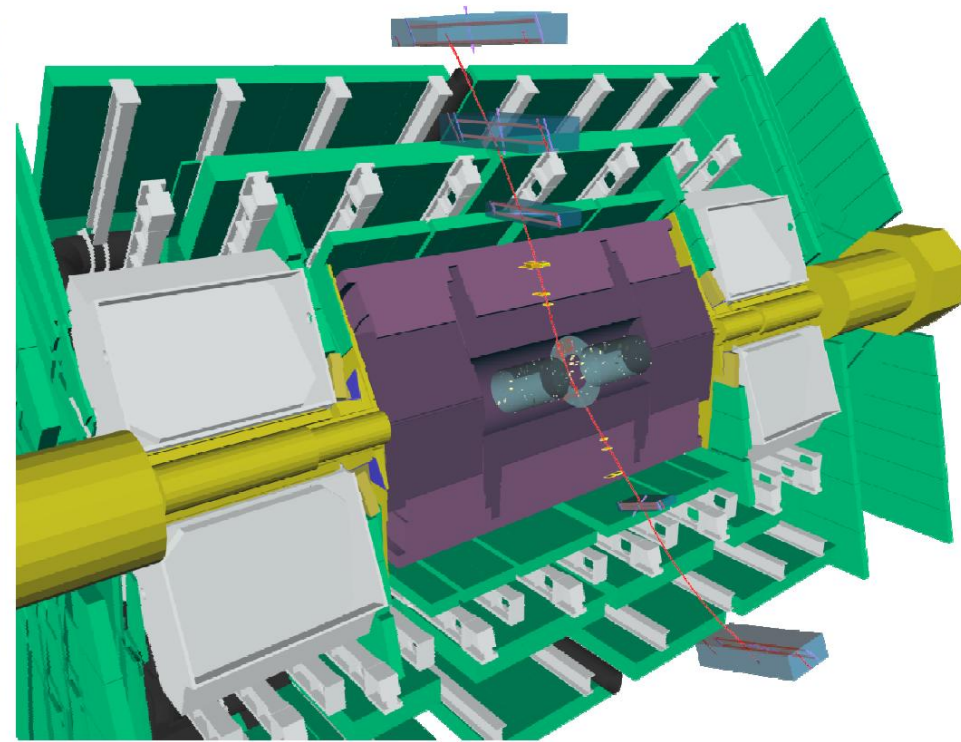
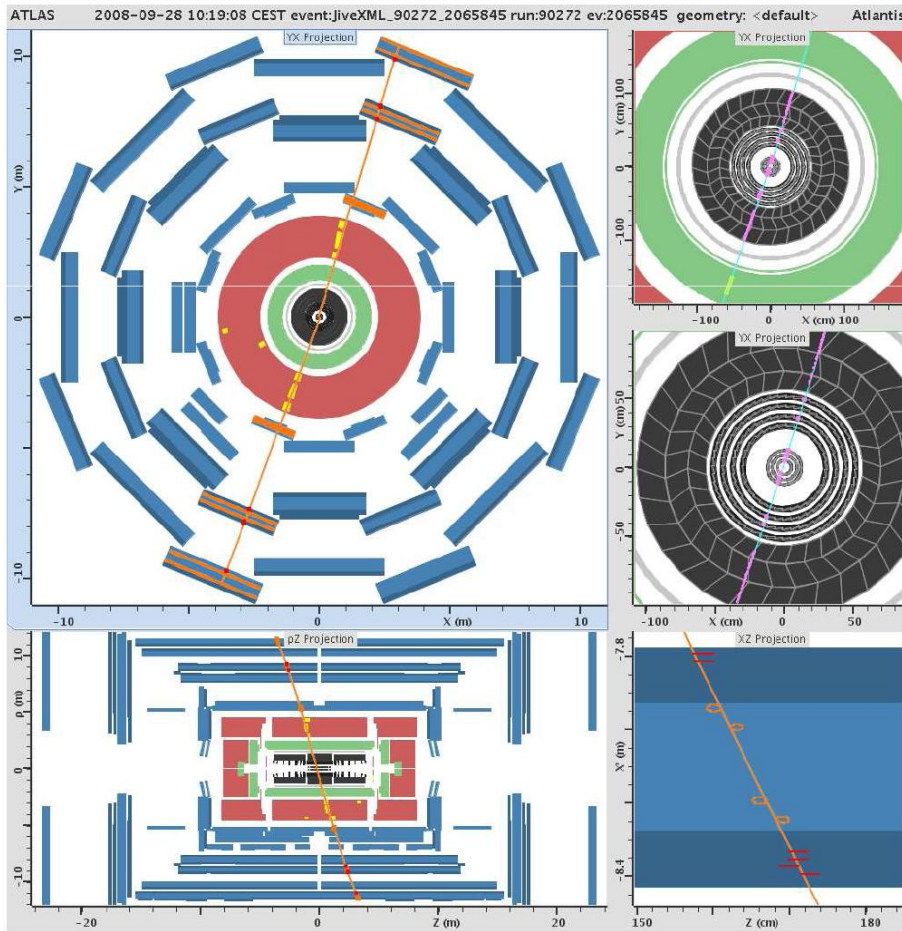
# Das erste LHC-Strahlereignis in ATLAS



first beam  
event seen  
in ATLAS

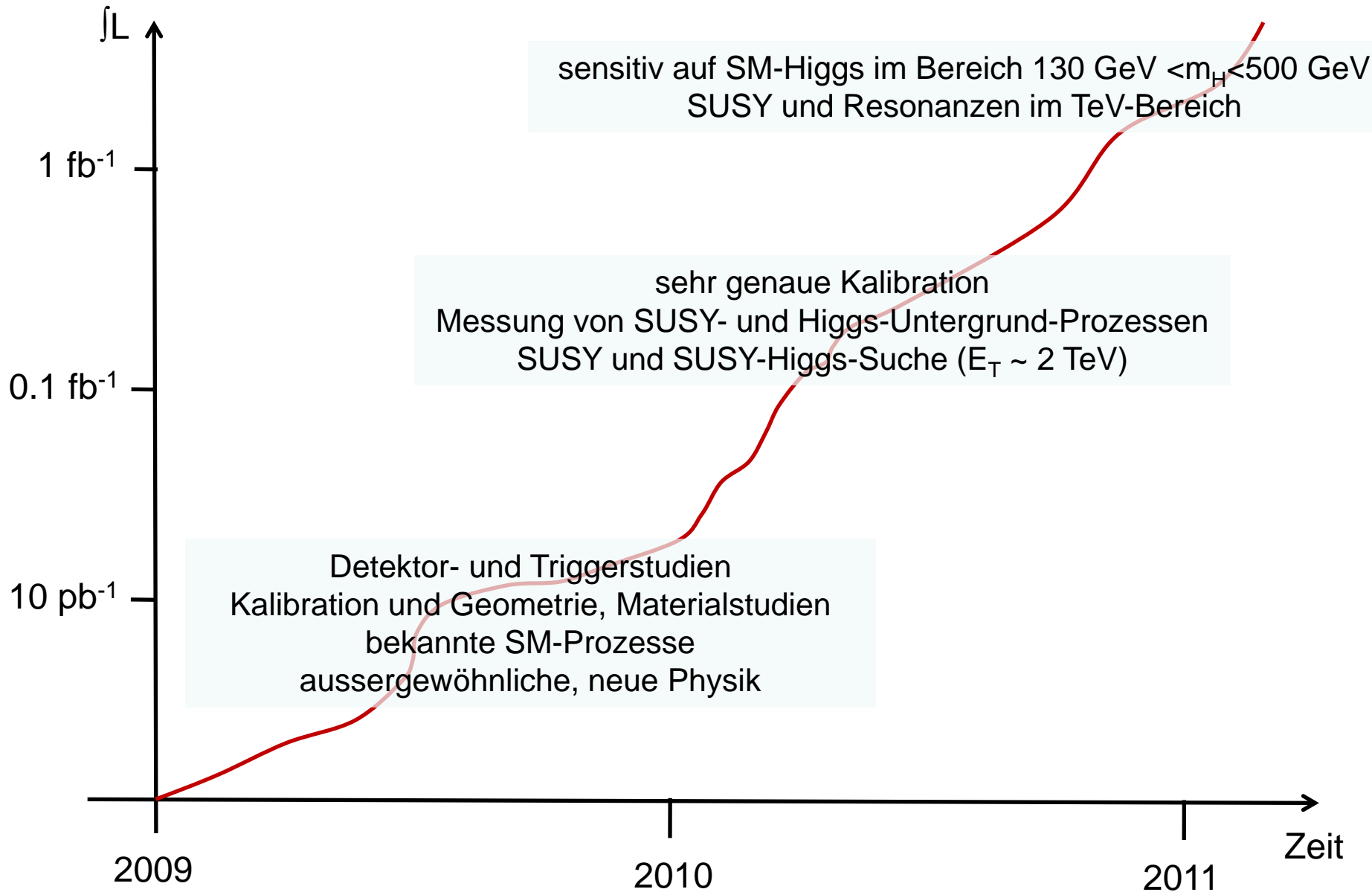
- September 2008
- Proton-Strahl trifft auf Kollimator → Teilchenschauer

- etwa 2 Millionen kosmische Trigger
- mit und ohne Magnetfeld



- z.B. Flüssig-Argon Kalorimeter:
  - Kalibration der Signal-Zeitmessung → Trigger und Zuordnung zu Strahlkreuzung
  - Korrektur der Signal-Höhe in Kalorimeter-Zellen mit HV-Problemen

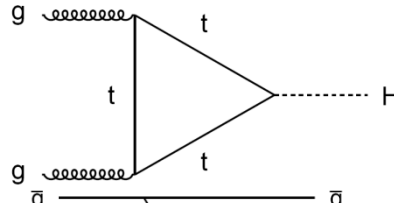




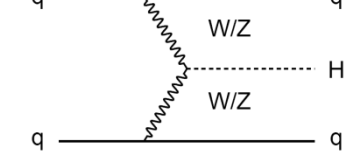
# Suche nach dem SM Higgs-Boson



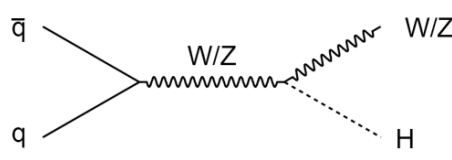
**Glukon-Glukon-Fusion**



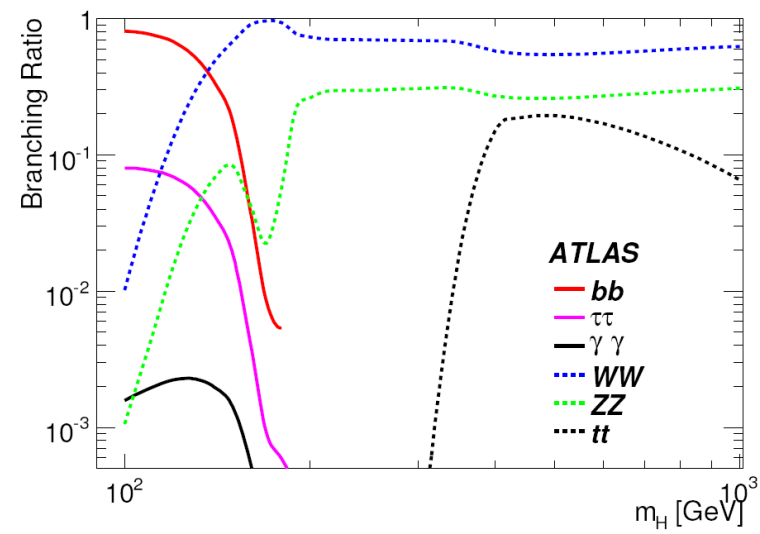
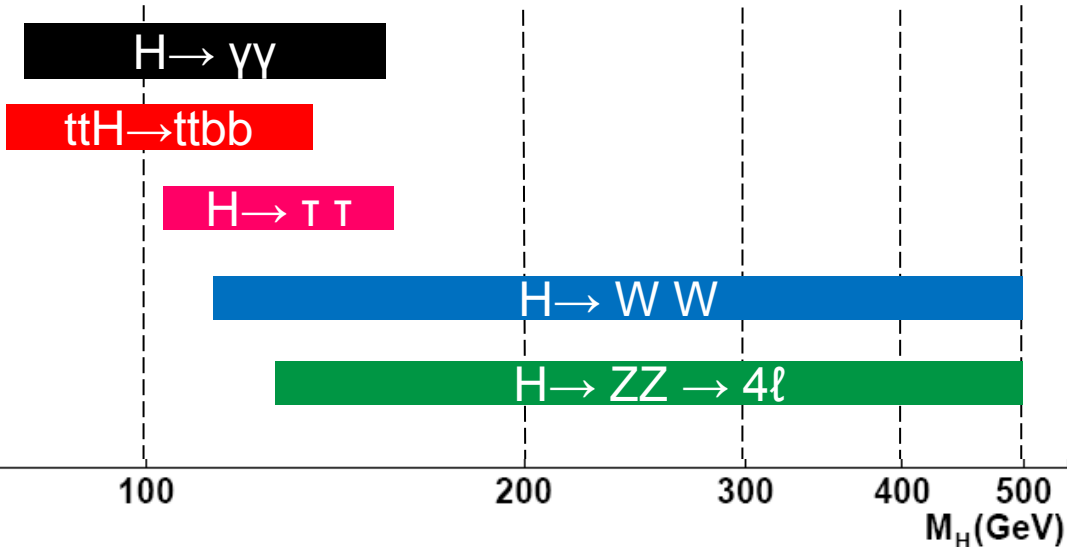
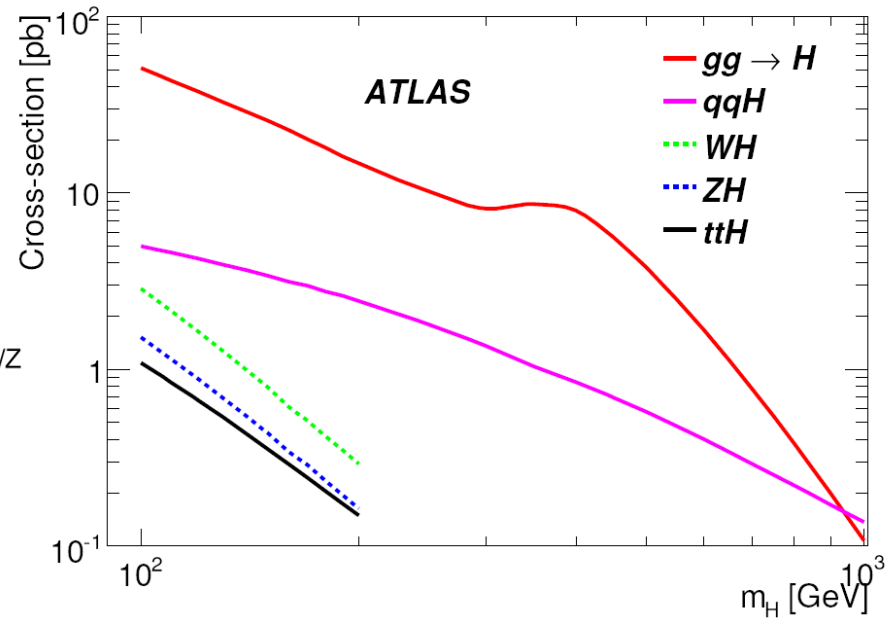
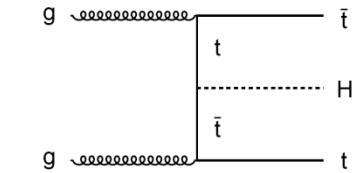
**Vektor-Boson-Fusion**



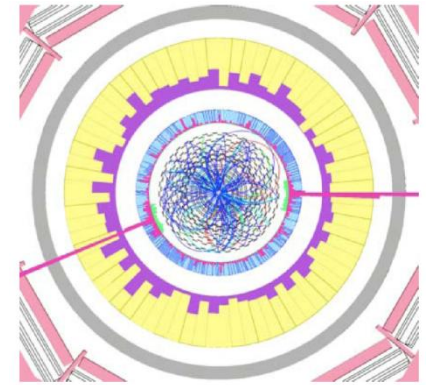
**Higgs-Strahlung mit W/Z**



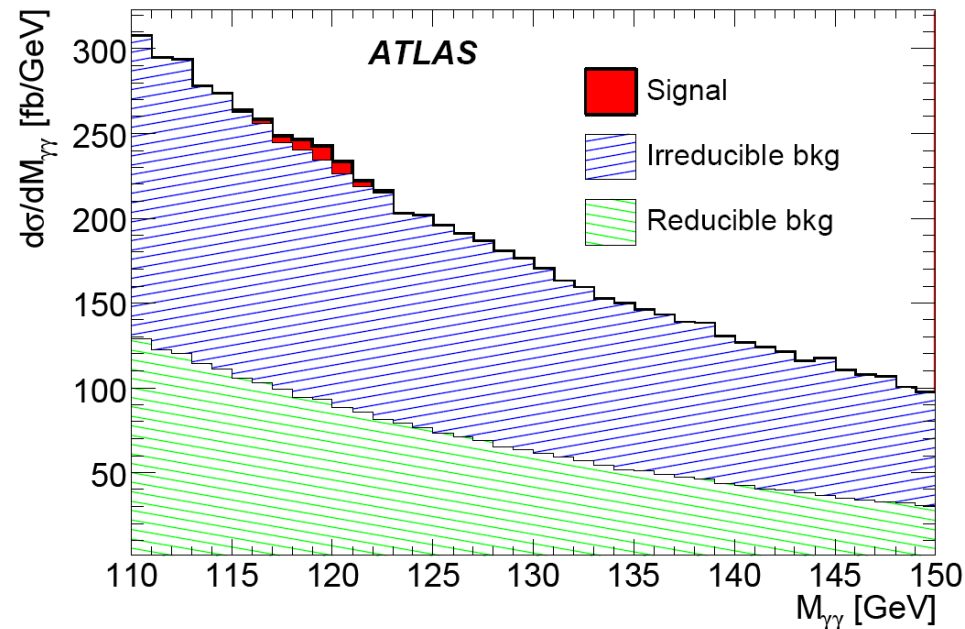
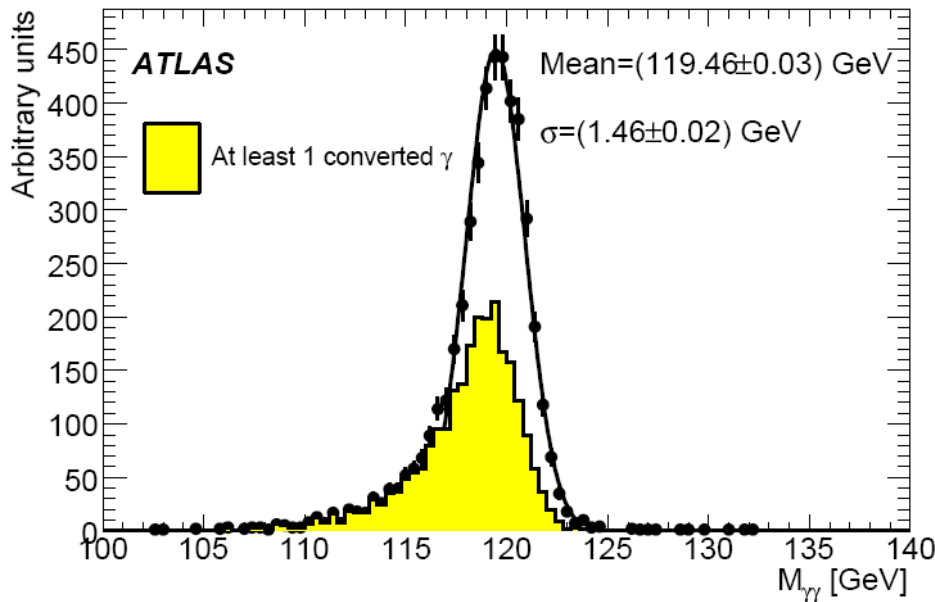
**assoziierte Produktion mit top-Quarks**



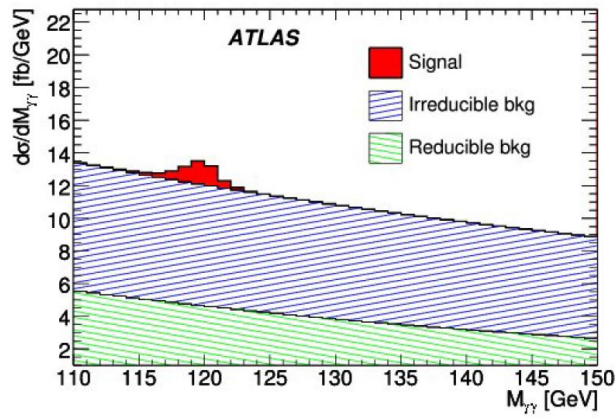
# H → γγ



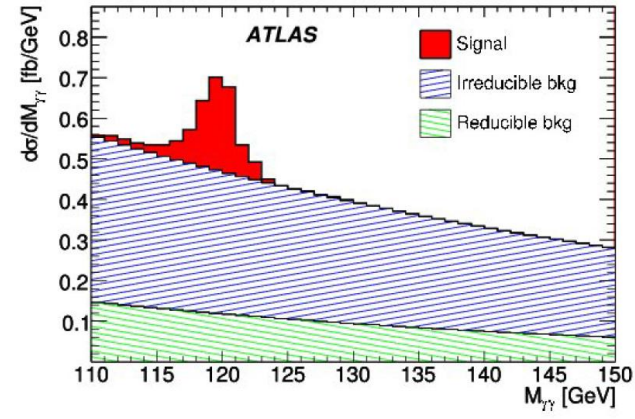
- Sehr gute  $M_{\gamma\gamma}$  Massenauflösung → 1.3%
- Untergrund:
  - QCD  $qq, qg, gg \rightarrow \gamma\gamma$  sieht genauso aus → irreduzibel
- benötigt gut verstandenes Kalorimeter und Spur-Detektoren
  - Energie-Kalibration
  - Rekonstruktion des Zerfalls-Vertex aus Schauerrichtung im Kalorimeter
  - Photon-Konversionen  $\gamma \rightarrow e^+e^-$



## H + 1 jet

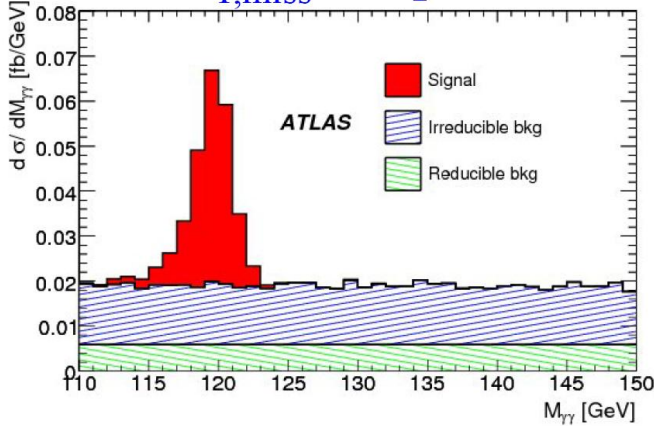


## H + 2 jets

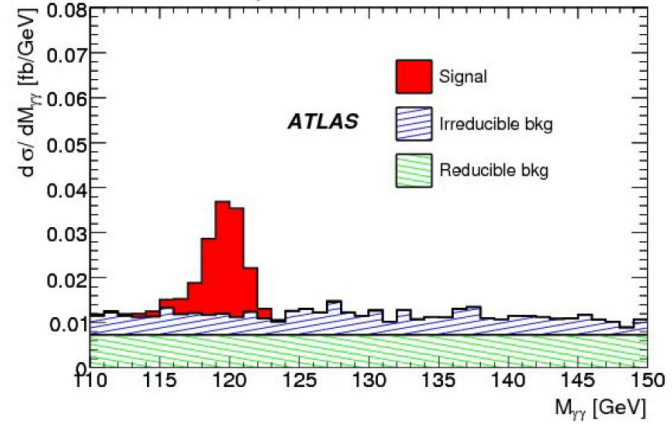


- Signal/Untergrund: inklusiv: 27/1000
- exklusiv  $\rightarrow$  1/1
- aber viel geringere Ereignisraten

## H + $E_{T,miss}$ + lepton



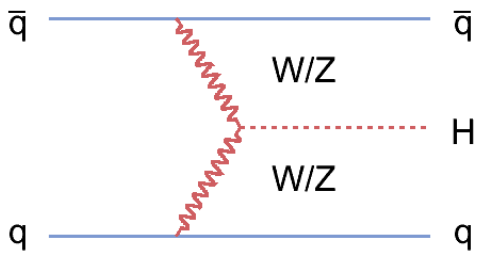
## H + $E_{T,miss}$



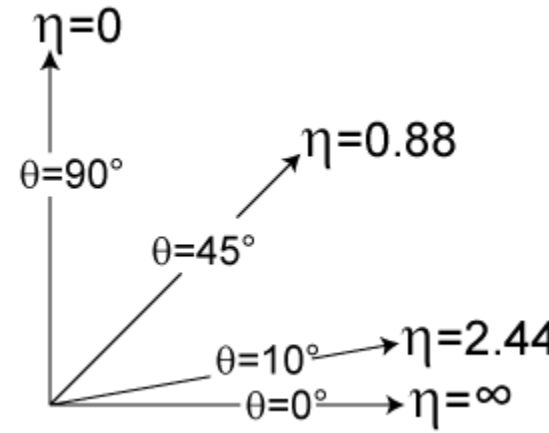
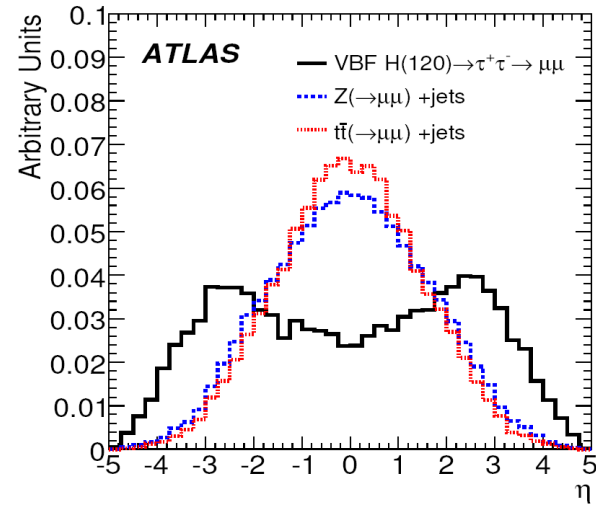
# Vektor-Boson-Fusion



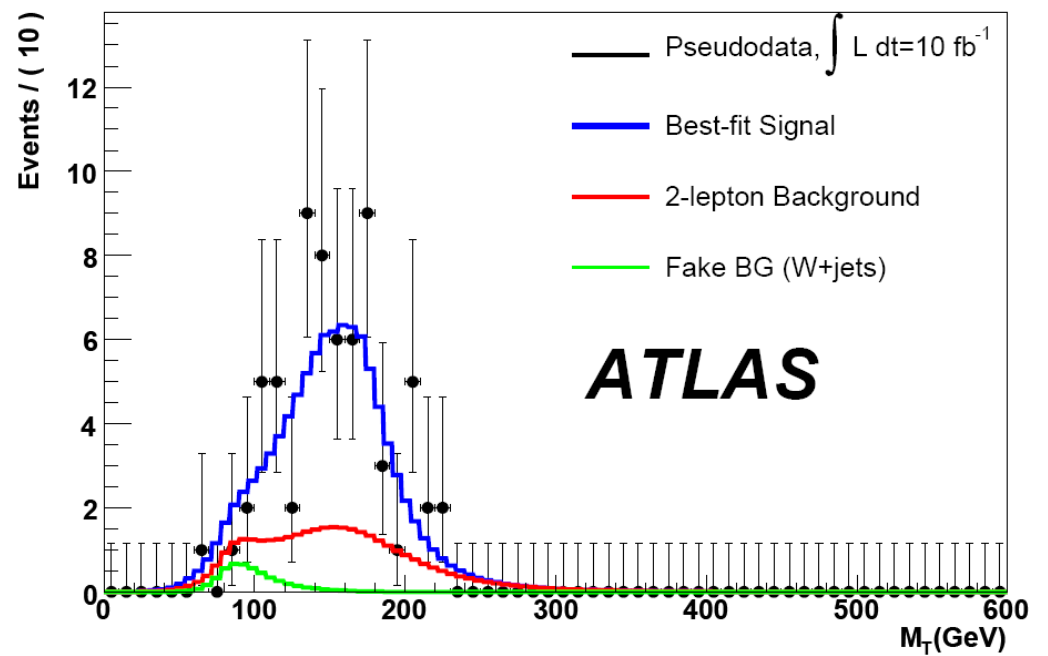
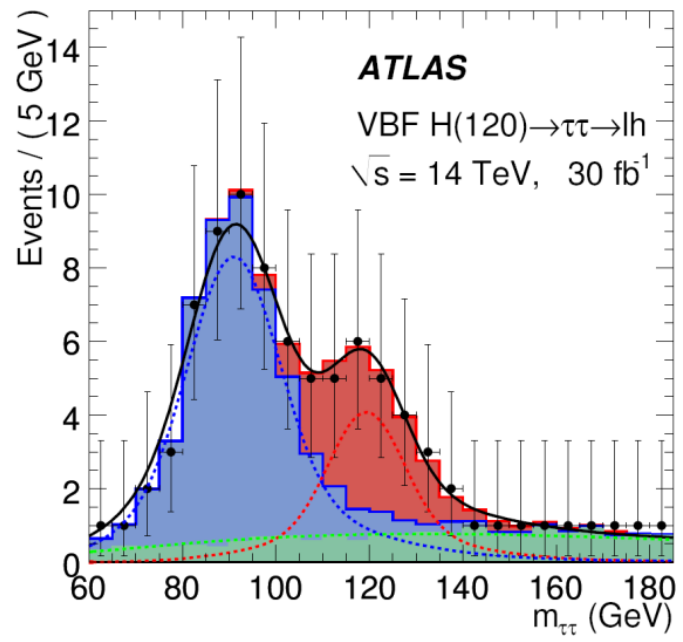
- 2 hadronische Jets in Vorwärtsrichtung:



- Rapiditäts-Lücke  $\Delta\eta_{jj}$

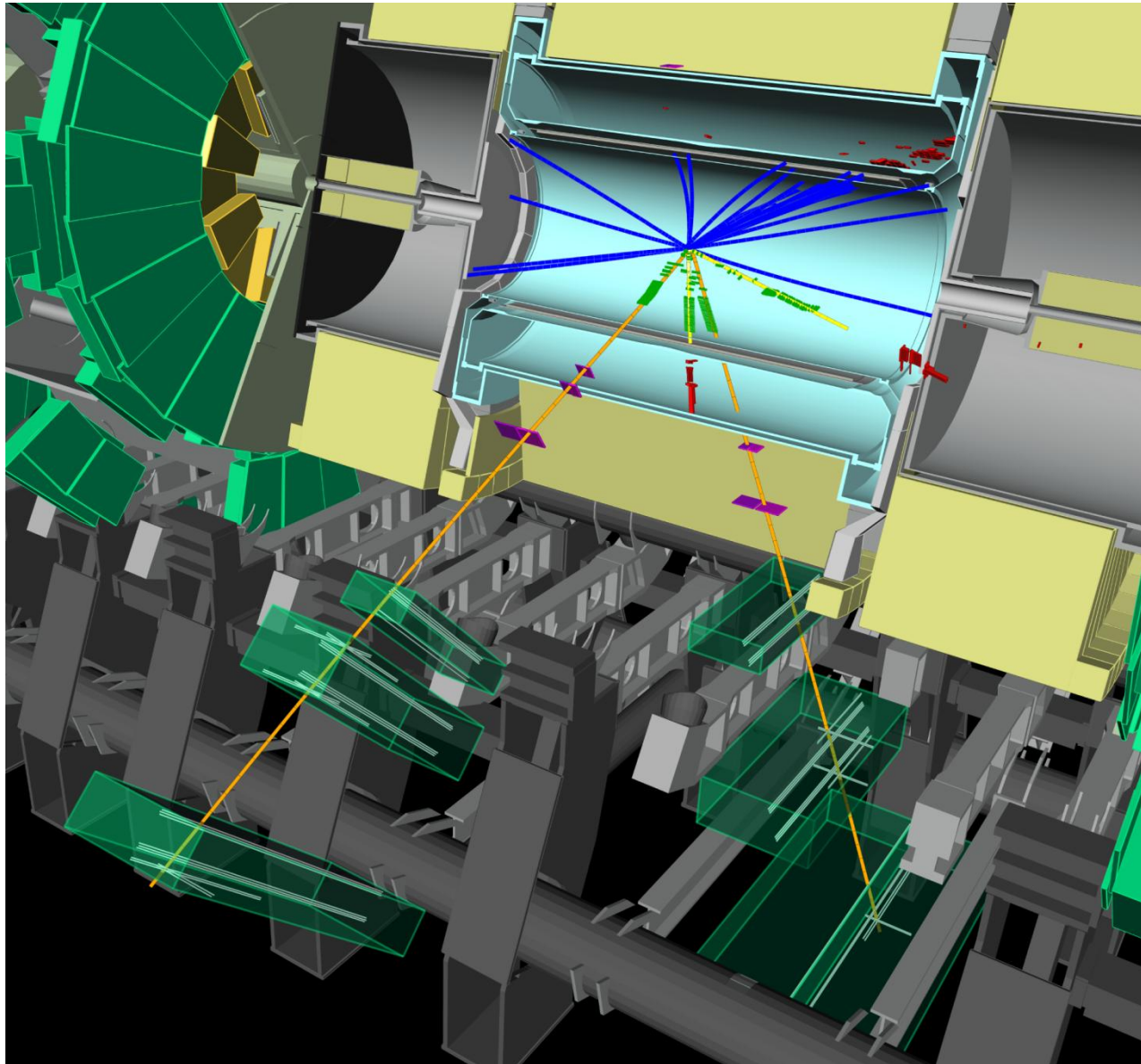


- $H \rightarrow \tau\tau + 2 \text{ Jets}$  und  $H \rightarrow WW \rightarrow e\nu\mu\nu + 2 \text{ Jets}$  aber auch  $gg \rightarrow H \rightarrow WW \rightarrow e\nu\mu\nu$





$$H \rightarrow ZZ \rightarrow 4\ell$$

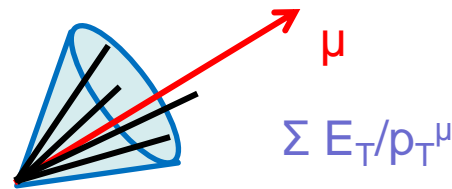
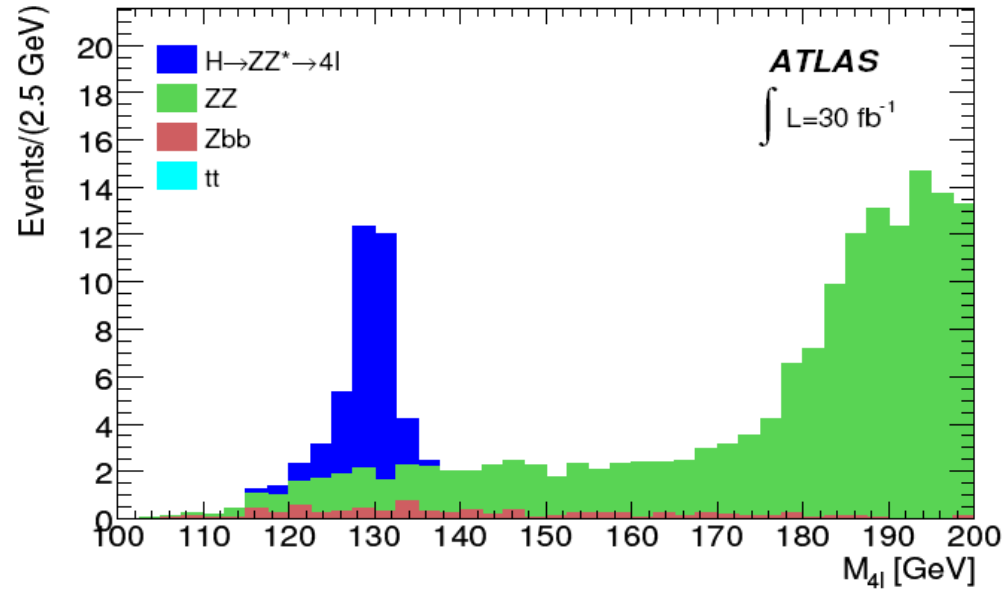
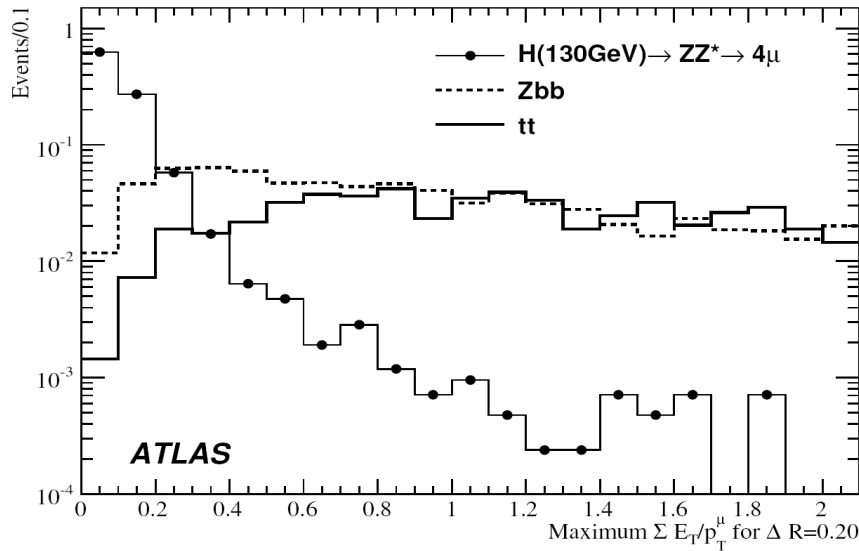
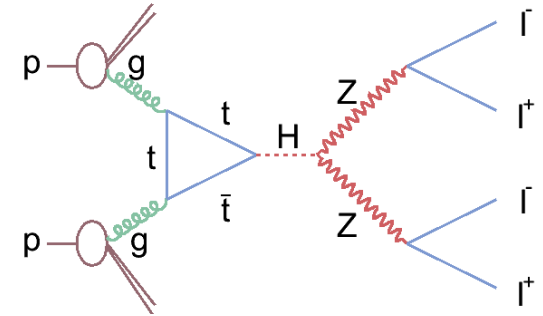


Simuliertes Ereignis  
 $H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$   
 mit  $m_H = 130 \text{ GeV}$



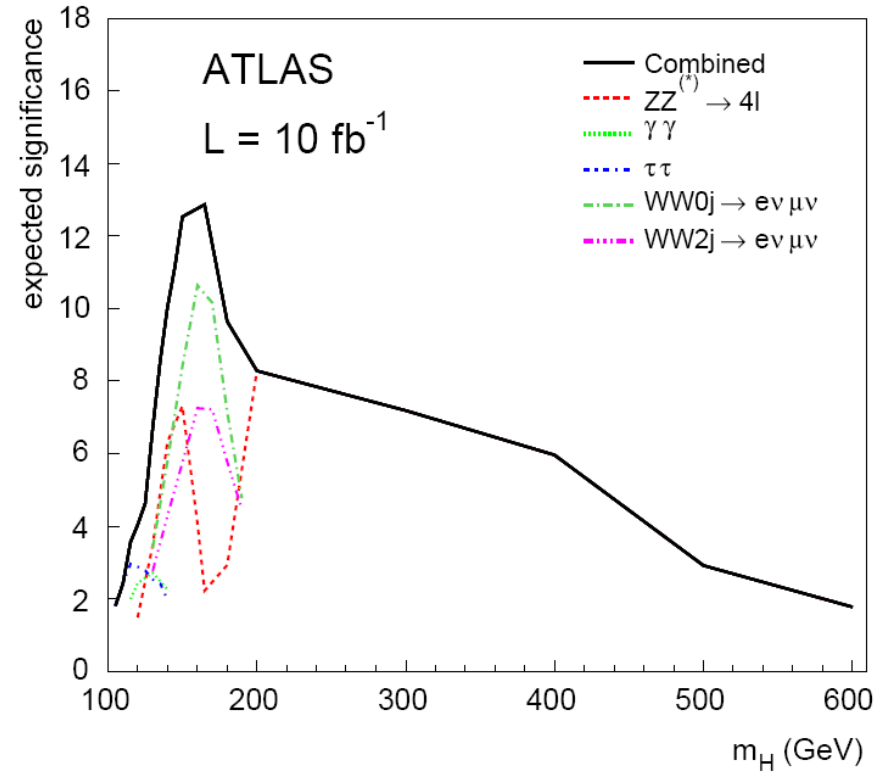
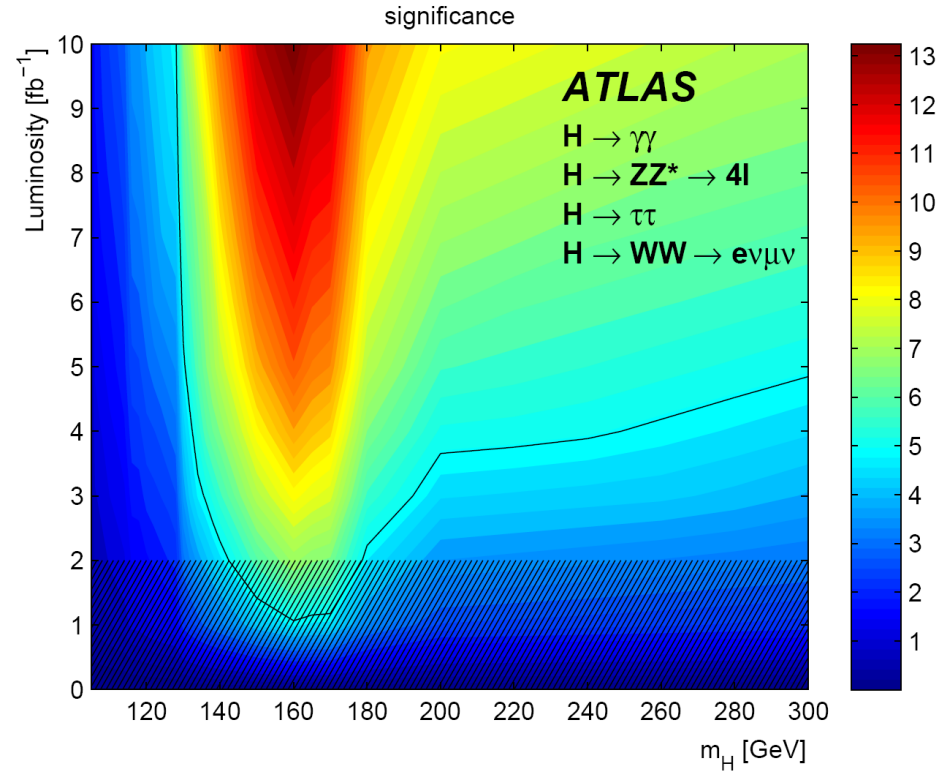
# $H \rightarrow ZZ \rightarrow 4\ell$

- "Goldener" Zerfallskanal:  $4\ell = e^+e^-e^+e^-, e^+e^-\mu^+\mu^-, \mu^+\mu^-\mu^+\mu^-$
- 4 Leptonen mit hohem Transveralimpuls
- Hauptuntergrund: ZZ-Produktion (irreduzibel)
- Rekonstruktion der Z-Masse(n)
- Leptonen isoliert von hadronischen Jets



• aktuell:  $H \rightarrow ZZ \rightarrow e^+e^-\tau^+\tau^-, \mu^+\mu^-\tau^+\tau^-$

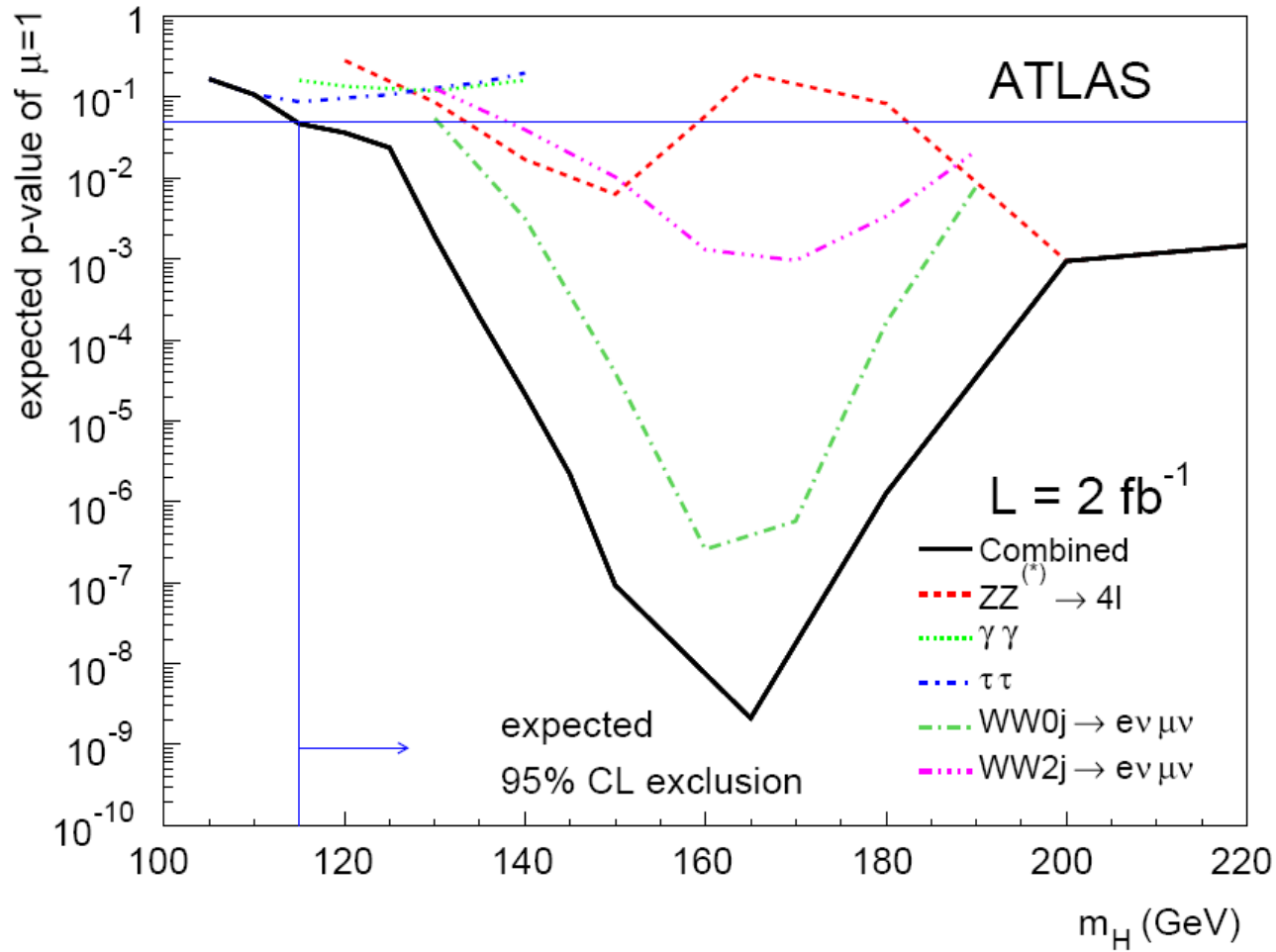




- mit  $2 \text{ fb}^{-1}$  kann das Higgs-Boson im Bereich  $m_H=143-179 \text{ GeV}$  mit  $5\sigma$  nachgewiesen werden

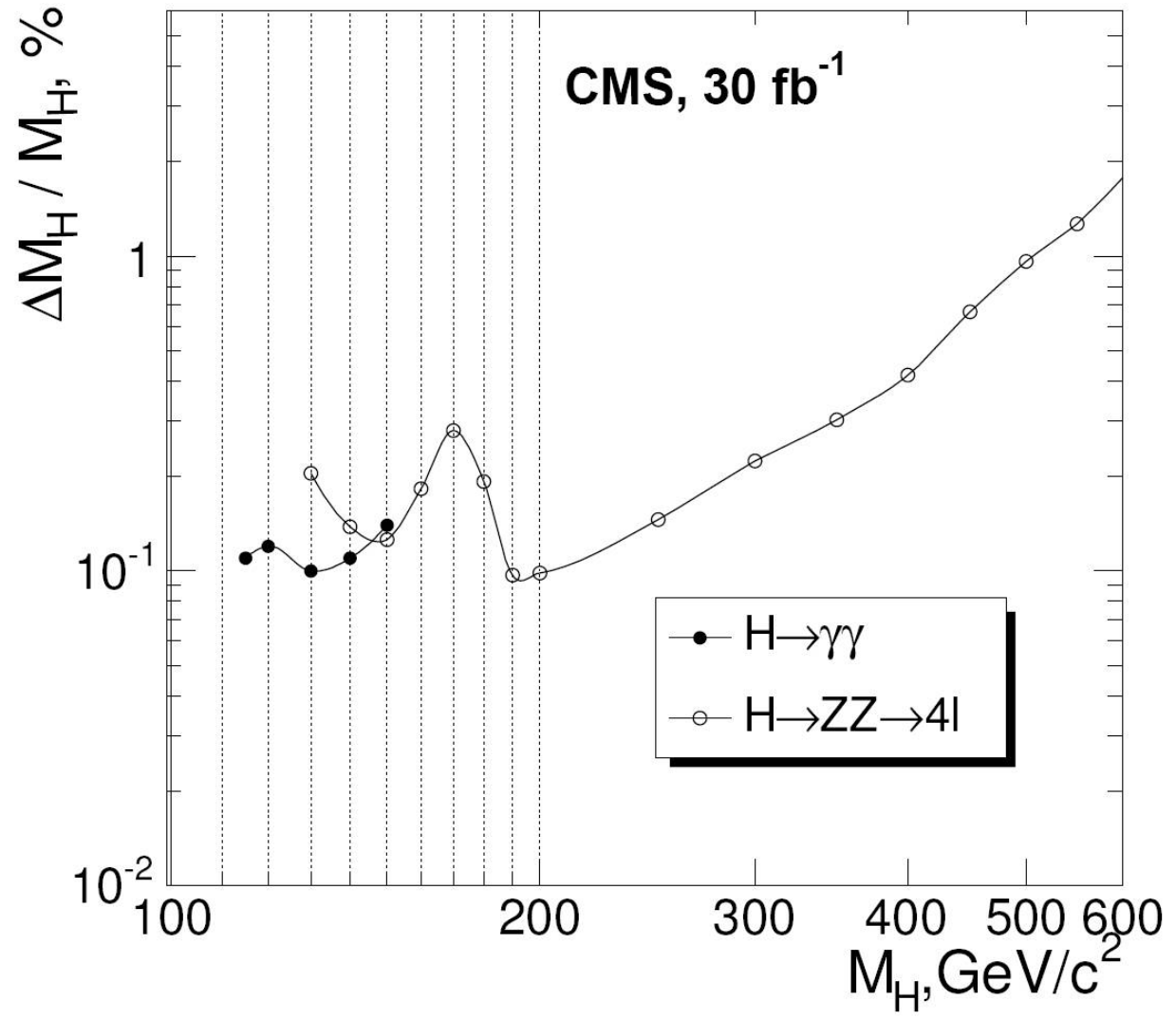
→ beachte: Tevatron!

# Falls kein Signal gefunden wird...



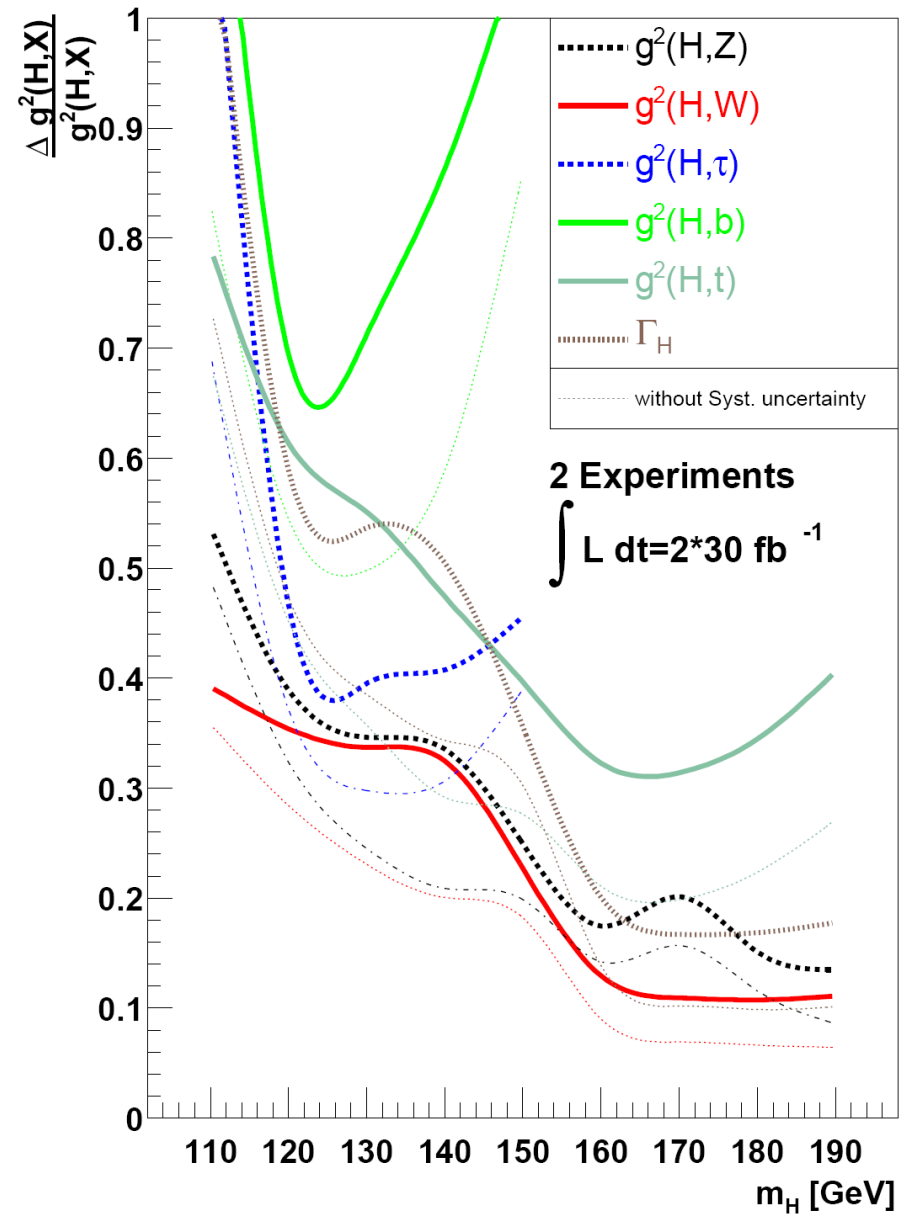
- Ausschlussgrenzen mit  $2 \text{ fb}^{-1}$ : 115 GeV bis 460 GeV

- Bestimmung der Higgs-Masse:



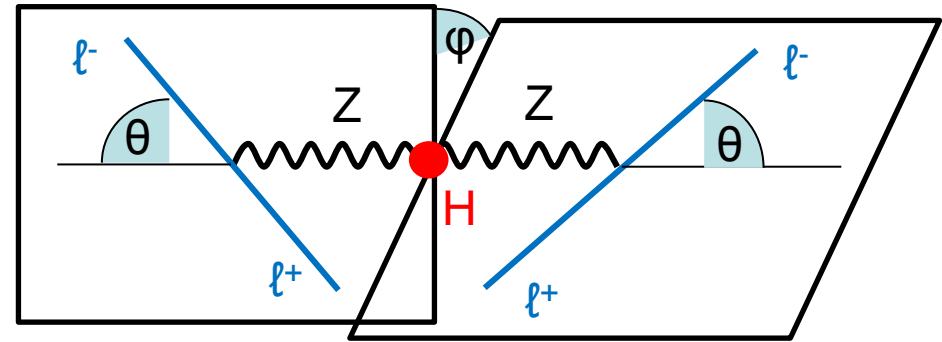
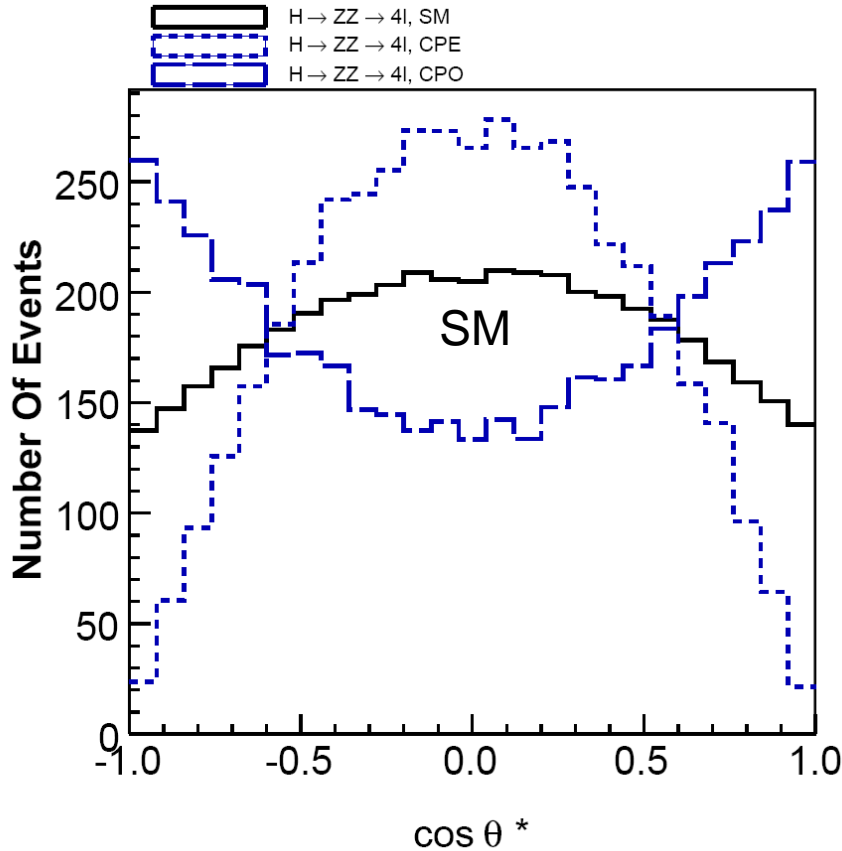
# Falls ein Signal gefunden wird...

- Messung der Higgs-Kopplungen
- nur mit Zusatzannahmen:
  - Higgs mit Spin 0
  - CP-gerade
  - Kopplungen wie im SM
  - $\Gamma_{H,tot} = \Gamma_{SM}$
- Kopplungen ohne Zusatzannahmen:  
→ Internationaler  $e^+e^-$  Linear Collider



# Falls ein Signal gefunden wird...

- Spin und CP-Eigenwerte aus Polarisation und Zerfalls-Winkel der Z-Bosonen



$$\frac{d\Gamma}{d\cos\theta}(Z_L \rightarrow ll) \propto \sin^2\theta$$

$$\frac{d\Gamma}{d\cos\theta}(Z_T \rightarrow ll) \propto 1 + \cos^2\theta$$

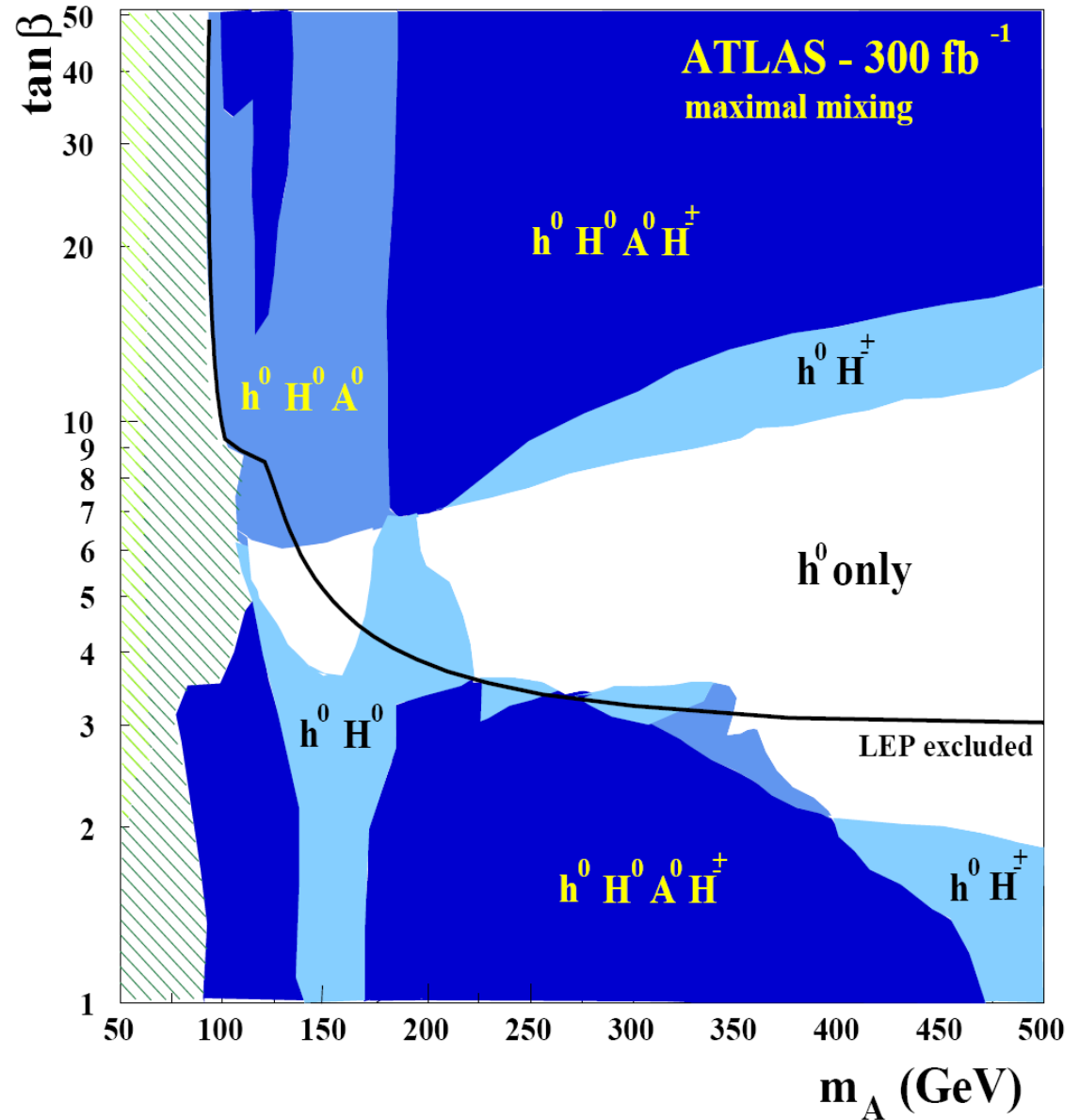
- mit  $100 \text{ fb}^{-1}$  kann Spin 1 ausgeschlossen werden ( $m_H > 230 \text{ GeV}$ )
- mit  $10\text{-}100 \text{ fb}^{-1}$  kann CP-ungerades Higgs ausgeschlossen werden (VBF oder  $H \rightarrow ZZ$ )



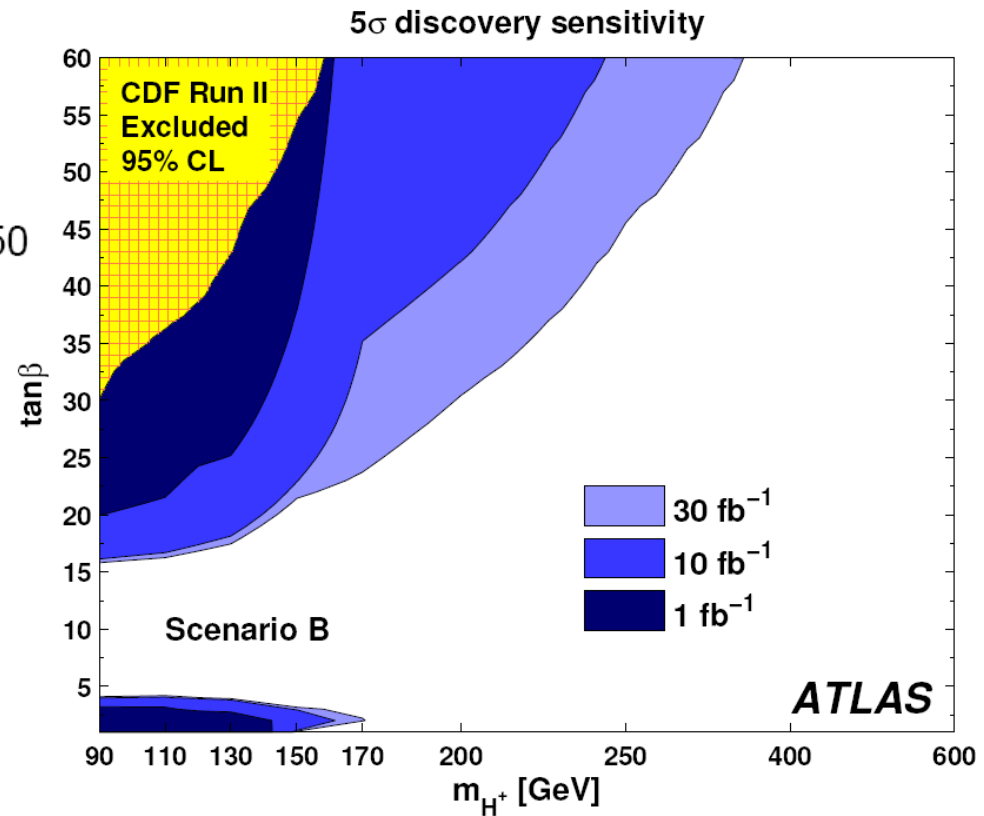
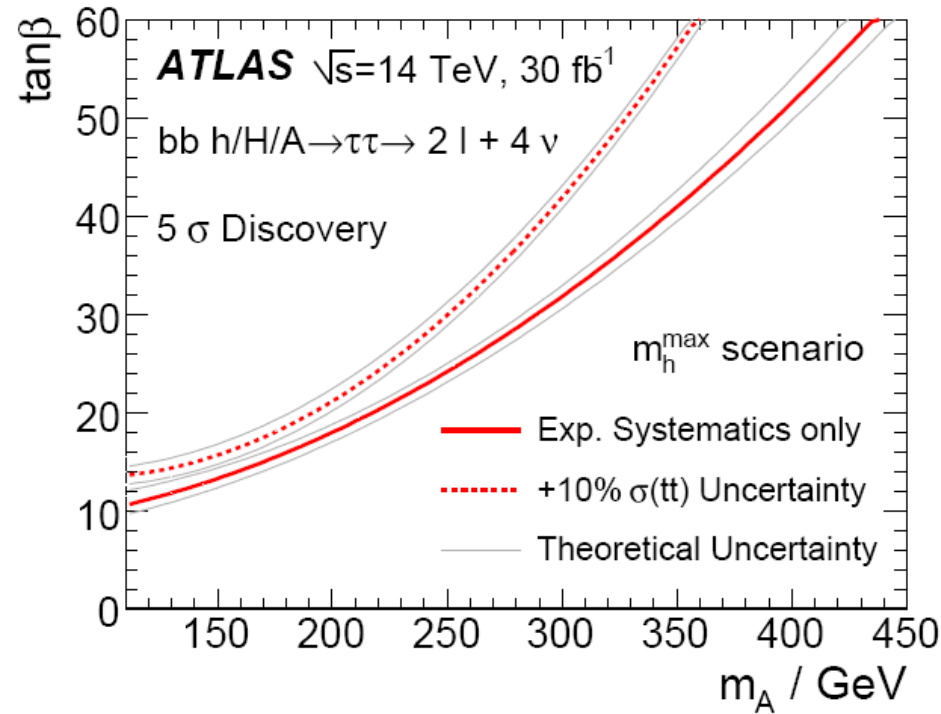
# Supersymmetrische Higgs-Bosonen



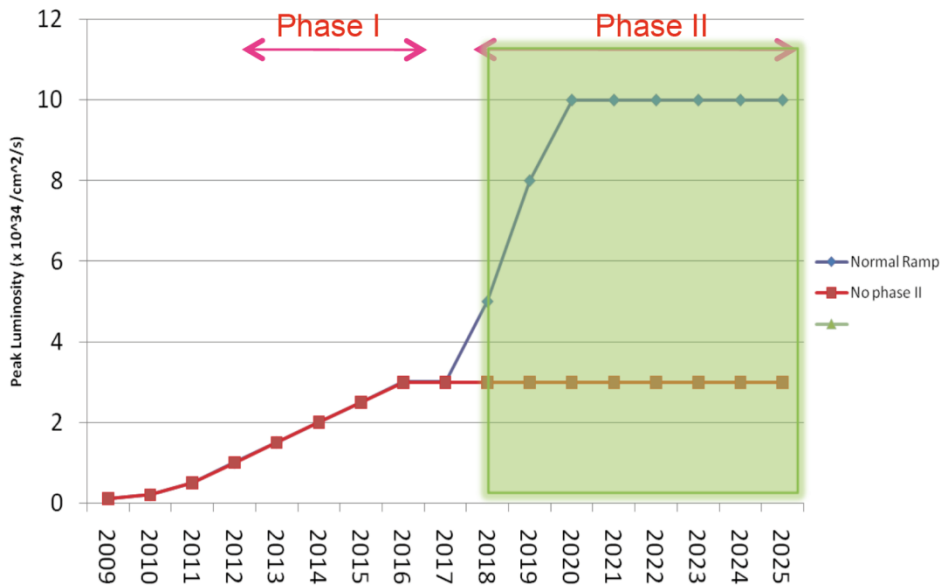
- $\tan\beta = v_2/v_1$   
Verhältnis der VEV der Higgs-Dupletts
- $m_A$  = Masse des CP-ungeraden Higgs
- in niedrigster Ordnung:  
 $m_h = m_h(m_A, m_Z, \tan\beta)$   
 $m_H = m_H(m_A, m_Z, \tan\beta)$   
 $m_{H^\pm} = m_{H^\pm}(m_A, m_W)$



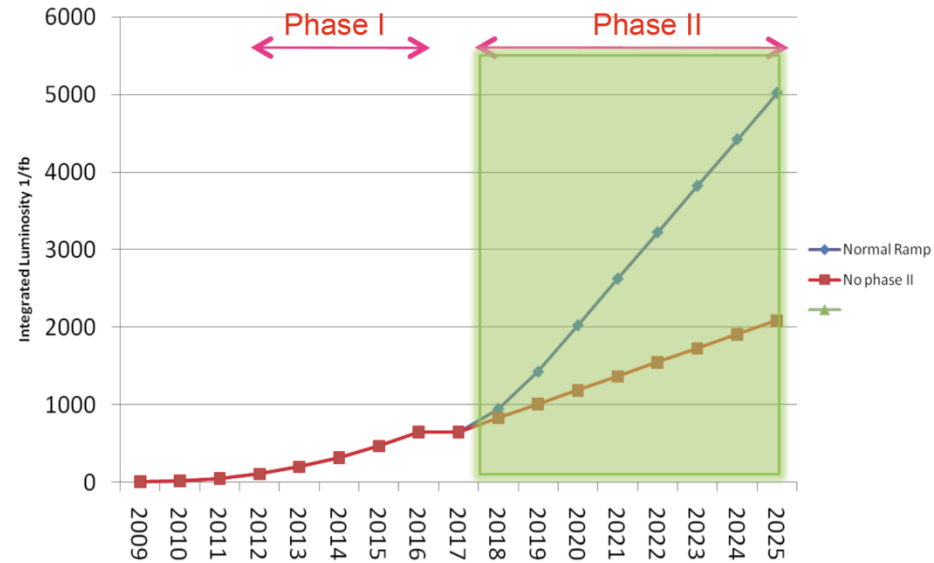
# SUSY-Higgs



- Instantane Luminosität [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]



- Integrierte Luminosität [ $\text{fb}^{-1}$ ]



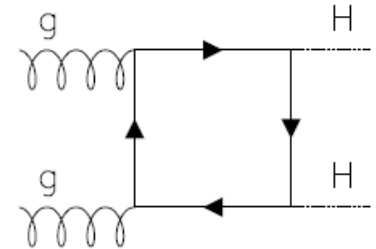
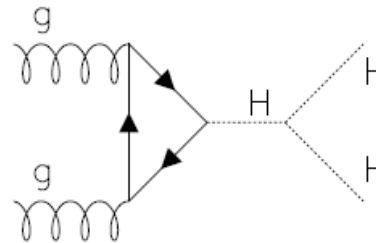
- noch seltenerere Ereignisse:

- eventuell  $HH \rightarrow WWWW, WWZZ$

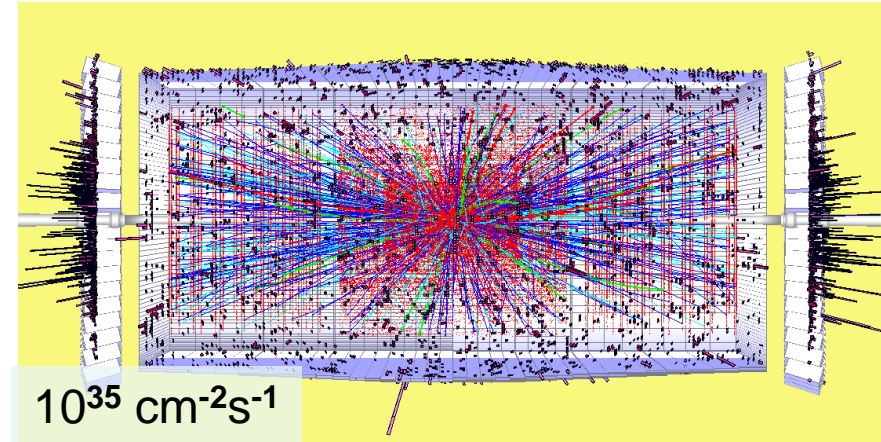
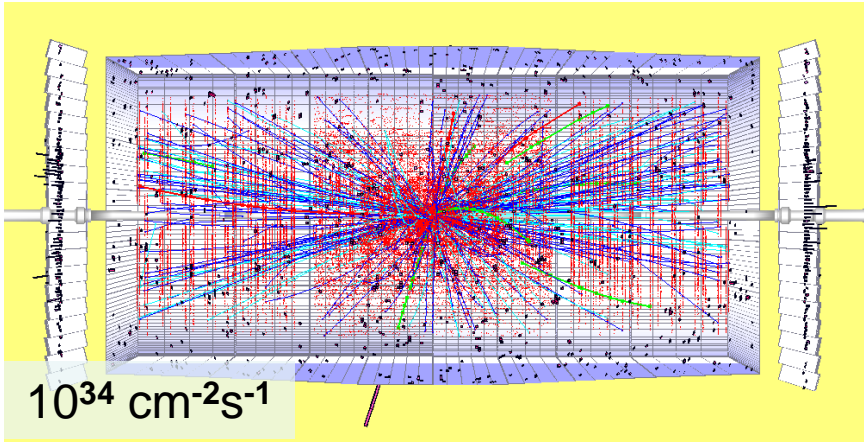
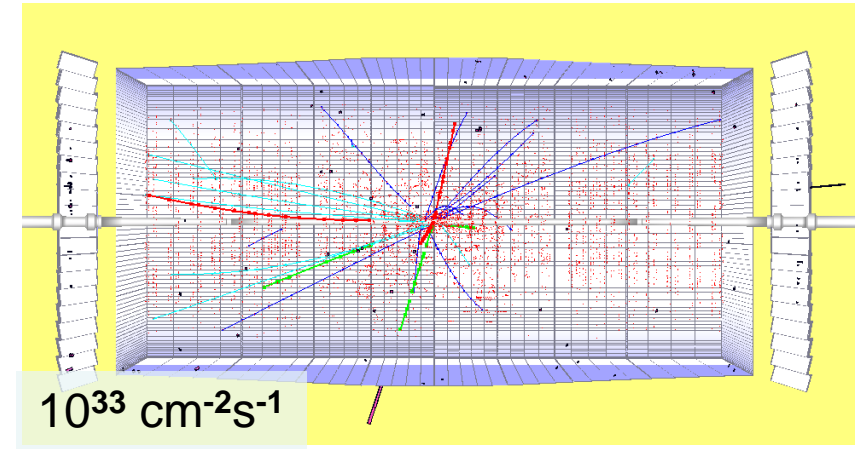
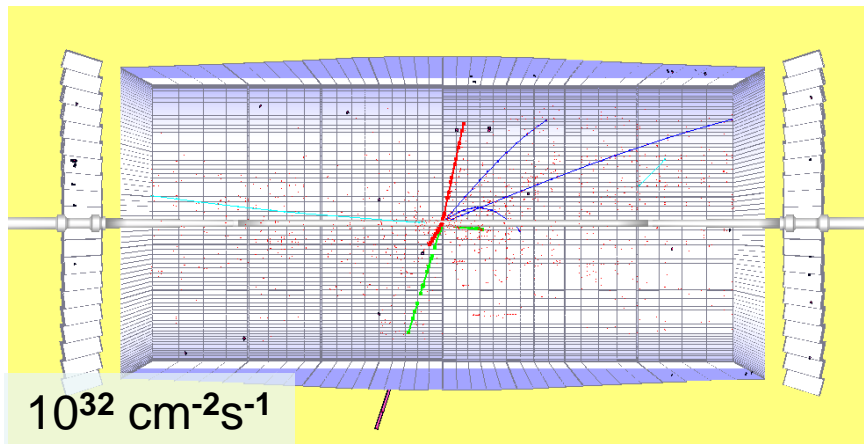
- mit  $6000 \text{ fb}^{-1}$ :

$$\Delta\lambda_{HHH}/\lambda_{HHH} \approx 25\% \text{ (stat)}$$

bei  $m_H=200 \text{ GeV}$



$H \rightarrow ZZ \rightarrow \mu\mu ee$  Ereignis mit  $m_H = 300$  GeV bei unterschiedlichen Luminositäten

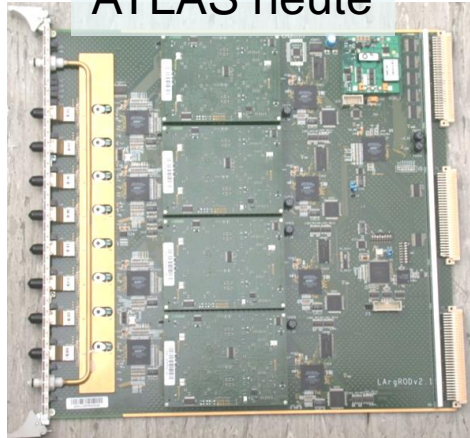


- nach Phase 1: Strahlenschädigung der Spur-Detektoren und der Detektor-Elektronik
  - Austausch der Pixel- und Silizium-Tracker und des Vorwärtskalorimeters
  - Neue Auslese-Elektronik der Kalorimeter

- 182468 Kanäle je 16 bit
- getriggert mit 100 kHz
- 1524 optische Links mit 1.6 Gb/s

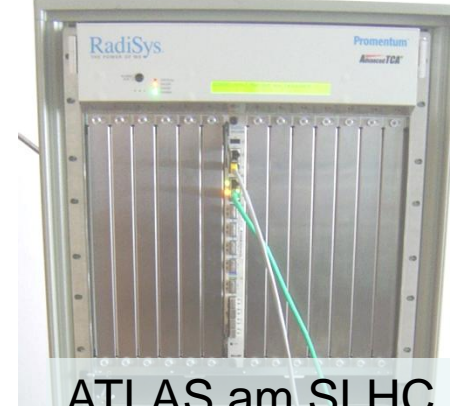
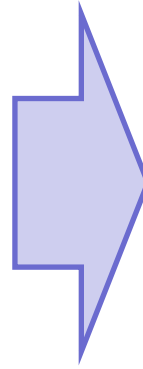


ATLAS heute



- Energie + Timing → Software-Trigger + DAQ

- 182468 Kanäle je 16 bit
- alle Ereignisse mit 40 MHz
- 1524 optische Links mit 100 Gb/s



ATLAS am SLHC / IKTP



- Energie + Timing → Hardware-Trigger + Software-Trigger + DAQ





- Das Higgs-Boson verleiht den Elementarteilchen Masse
- Entdeckungspotential des LHC mit  $1\text{-}30\text{ fb}^{-1}$ :
  - vom LEP-Limit  $114.4\text{ GeV}$  bis  $1\text{ TeV}$
- mit ähnlicher Datenmenge → Supersymmetrische Higgs-Bosonen
- mit viel Luminosität → Eigenschaften des Higgs-Bosons
- mit sehr viel Luminosität → evtl. Higgs-Selbstkopplung





# Beliebtheits-Skala der Elementarteilchen



The PARTICLE ZOO

Particle Sales 2008: **VISUAL SCALE**  
(particle sizes correspond to relative number sold)



"antimatter doesn't sell particularly well. The Higgs is the real top-seller and second place is dark matter. The charm quarks are very popular at Valentine's day because they are pink and have a rose."

Julie Peasley, CERN Bulletin, June 2009

→ Joseph Lykken – Dark Matter at the LHC 23.6.09